

**Clinical Application of Cross-Education to Unilateral Limb
Immobilization**

A Thesis Submitted to the College of
Graduate Studies and Research
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in the College of Kinesiology
University of Saskatchewan
Saskatoon

By

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Abstract

Cross-education is a neural adaptation defined as the increase in strength or functional performance of the untrained contralateral limb after unilateral training of the opposite homologous limb. Since cross-education can improve strength in an untrained limb, there is therapeutic potential to apply cross-education to clinical rehabilitation settings; however, a large gap in the literature remains. The first objective of this thesis was to determine if cross-education could improve strength and functional performance (i.e. active range of motion (AROM), self-reported function) of an immobilized limb using a shoulder sling model in both healthy and injured participants. The second objective was to determine if cross-education could improve strength and functional performance (i.e. AROM, self-reported function) of wrist fracture rehabilitation after unilateral training of the non-fractured limb. **Study 1** applied cross-education to non-injured participants who wore a shoulder sling and swathe and strength trained the non-immobilized limb. Strength (NORM dynamometer), muscle size (ultrasound), electromyography, and interpolated twitch were measured. Results showed cross-education increased strength and maintained muscle size in the immobilized limb after training the non-immobilized limb. **Study 2** applied cross-education using a clinically relevant at-home resistance tubing shoulder strength training program to healthy participants. Results showed significant cross-education effects for untrained shoulder external and internal rotation strength (handheld dynamometer), and increased muscle size (ultrasound) in the trained supraspinatus and anterior deltoid. **Study 3** applied cross-education using the clinically relevant strength training program (in Study 2) to post-shoulder surgery rehabilitation and measured strength (handheld dynamometer), muscle size (ultrasound), AROM (goniometer), and self-reported function (Western Ontario Rotator Cuff Questionnaire) (WORC). Results showed the training group had

significantly greater supraspinatus muscle thickness at 6 months post-surgery compared to the control group; however, there were no cross-education effects for strength, AROM, or the WORC. **Study 4** applied cross-education during rehabilitation from wrist fractures and measured strength (handgrip dynamometer), AROM (goniometer), and self-reported function (Patient Rated Wrist Evaluation) (PRWE). Results showed cross-education improved strength and AROM in the fractured limb 12 weeks post-fracture. In conclusion, there was evidence for cross-education to benefit a healthy immobilized limb and to use a clinically relevant shoulder strength training program to produce cross-education effects. When cross-education was applied to shoulder surgeries there were improvements in muscle size but no effect for strength, AROM or function. However, when applied to wrist fractures, strength and AROM were improved for the injured limb. These findings represent the first well-controlled evidence that cross-education may improve rehabilitation after unilateral injuries.

Acknowledgements

I would first like to acknowledge my supervisor, Jon Farthing for all of his guidance throughout the years. Jon and I began working together in my undergraduate degree and continued throughout my Masters and my Ph.D. Jon has put many hours into teaching me, including multiple long-lasting stats sessions. I am sure we will both cringe whenever we hear the letters “MCAR”. Thank you Jon, without your guidance, I would not be where I am today. I would like to thank my committee for all of their input throughout my program, and would also like to thank my lab mates (Joel Krentz, Trevor Barss, and Kellie Boychuk) for all of the hours they spent helping me with my studies. I would like to acknowledge my funding sources, including NSERC, the College of Kinesiology, the College of Graduate Studies, the Saskatchewan Sports Medicine Council, and the RUH foundation. Finally, I would like to acknowledge the participants who volunteered their time to assist in my research.

Dedication

This thesis is dedicated to my family, and my fiancé, John. My family has truly supported and encouraged me throughout my graduate program. They have helped motivate me through the more difficult and stressful times, and have kept me on track to finishing my program. I would like to especially thank my parents, Clint and Marlene for their continued support. I am sure my university years lasted a bit longer than they anticipated, but their endless encouragement helped inspire me to pursue an academic career. John, my fiancé has helped me like no one else. John has been so understanding of everything, including all the overtime hours I have put into my thesis, and has offered me endless support. I cannot thank John, and my family enough for all they have done. I would not be where I am today without any of you.

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List of Abbreviations

ANCOVA – Analysis of covariance

ANOVA - Analysis of variance

CEP – Certified Exercise Physiologist

CMRR - Common mode rejection ratio

EMG – Electromyography

ES – Effect size

fMRI – Functional magnetic resonance imaging

ICC – Intraclass correlation coefficient

ITT – Intention-to-treat

MANOVA – Multivariate analysis of variance

MAV – Mean absolute value

MCAR - Missing completely at random

MCID – Minimal clinically important difference

MEP – Motor evoked potential

PPT – Physical performance test

pQCT – peripheral quantitative computed tomography

PRWE - Patient Rated Wrist Evaluation

AROM – Active range of motion

SD – Standard deviation

SE – Standard error

TMS – Transcranial magnetic stimulation

VAS – Visual analog scale

WHQ - Waterloo handedness questionnaire

WORC – Western Ontario Rotator Cuff

List of Definitions

Cross-education - a neural adaptation defined as the increase in strength or functional performance of the untrained contralateral limb after unilateral training of the opposite homologous limb.

Function – the restoration to normal abilities after an injury.

Immobilization – limiting movement of a body part (i.e. a cast).

Minimal Clinically Important Difference - the minimum change in a score that indicates a meaningful difference for the patient.

Motor Learning – the process of improving motor skills.

Range of Motion (ROM) – the amount of movement in specific a joint.

Active range of motion (AROM) – the amount of movement in a specific joint using only the muscles around that joint to produce the movement.

Rehabilitation –the treatment(s) designed to facilitate the process of recovery from an injury.

Scaption - abduction of the extended arm in the scapular plane, 30 degrees anterior from the coronal plane.

Strength – the amount of force that a muscle or group of muscles can produce.

Chapter 1: Introduction and Review of the Literature

1.1 Introduction

Cross-education is defined as the increase in strength or functional performance of the untrained contralateral limb after unilateral training of the opposite homologous limb (Farthing et al., 2005; Carroll et al., 2006). Cross-education may also be referred to as cross-transfer, the contralateral strength training effect or the cross-training effect. It was first discovered by Scripture et al. (1894), and has been investigated for over a century. Typical effects are shown after a conducting a unilateral strength training program (ranging from 4-12 weeks in duration) (Zhou, 2000) on one limb. The increase in strength in the untrained limb is related to the gain in magnitude of the trained limb, and is on average 52% of the strength gain observed in the trained muscle (Carroll et al., 2006). Cross-education has been demonstrated in both males and females (Kannus et al., 1992) and in a variety of tasks in both upper (Farthing et al., 2005; 2009) and lower limbs (Hortobágyi et al., 1997). Typically, greater effects are shown with more novel or unfamiliar strength tasks (Farthing, 2009). Cross-education is thought to be primarily controlled by neural mechanisms (Carroll et al., 2006; Lagerquist et al., 2006; Farthing et al., 2007; Fimland et al., 2009; Farthing et al., 2011; Hortobágyi et al., 2011); however, the exact mechanisms are unknown.

Since cross-education can improve strength in an untrained limb, it has obvious potential for therapeutic benefits such as rehabilitation after unilateral injuries. Numerous studies have identified the potential of cross-education in rehabilitation; however, a large gap in the literature remains in applying cross-education to clinical settings. As yet there are no well-controlled studies that have applied cross-education to real injury rehabilitation. There is only 1 study to date that has attempted to apply cross-education to real injury rehabilitation (Stromberg, 1986;

1988) (reports from the same data set); however, large limitations make it very difficult to draw any conclusions from the results. Farthing et al. (2009; 2011) applied cross-education to a forearm casting model using non-injured participants and showed beneficial effects in the immobilized, untrained limb, yet there have been no studies that have verified these findings in a model other than forearm casting (i.e. prior to Study 1 of this thesis; Magnus et al. 2010).

With the large gap in the literature, and therapeutic potential for application of cross-education to clinical rehabilitation settings, there is a need for more research to determine how cross-education can be applied to injuries. Therefore, two main objectives are described in this document. The primary objective was to determine if cross-education could improve strength and functional performance (i.e. active range of motion (AROM), self-reported function) of an immobilized limb using a shoulder sling model in both healthy and injured participants. The second objective was to determine if cross-education could improve strength and functional performance (i.e. AROM, self-reported function) of wrist fracture rehabilitation after unilateral training of the non-fractured limb. Four experiments were necessary to meet these objectives. Three studies in this document were intended to investigate if cross-education can be applied to unilateral limb immobilization using a shoulder sling. The purpose of the first study was to apply cross-education to unilateral limb immobilization using a shoulder sling and swathe model in non-injured participants to determine if cross-education would benefit the immobilized limb. The second study examined if a clinically relevant at-home shoulder strength training program using resistance tubing was feasible to produce cross-education effects in the untrained limb. The third experiment aimed to apply the clinical at-home shoulder strength training program to a real injury setting using shoulder surgery participants to determine if cross-education strength training could improve rehabilitation after shoulder surgery. The final study also involved

injured participants, and aimed to investigate if cross-education could benefit wrist fracture rehabilitation after strength training the non-fractured limb.

1.2 Review of the Literature

1.2.1 Cross-Education

Scripture (1894) was the first to document cross-education when one participant, Miss Emily M. Brown strength trained her right hand with handgrip contractions using a rubber bulb. Strength was measured by connecting the rubber bulb to a manometer. Her training program consisted of 10 repetitions over 8 training sessions in 13 days. Scripture showed that training of the right hand resulted in an increase in strength of 43% in the left hand. Since its discovery in 1894, many studies have investigated cross-education, yet criticism has been received as to whether the transfer in strength from the trained to untrained limb actually exists. In the past, cross-education literature has been questioned for its methodology due to small sample sizes and lack of a control group (Munn et al., 2004). The majority of literature shows cross-education improves strength in the opposite, untrained limb; however, there are some studies that have not shown an effect (Gardner, 1963; Meyers, 1966; Garfinkel & Cafarelli, 1992; Housh et al., 1992). A meta-analysis completed by Munn et al. (2004) combined the findings of 13 randomized, controlled cross-education studies that used maximal voluntary strength training. The meta-analysis concluded that the pooled cross-education effect increased strength 7.8% in the untrained limb, and transferred 35% of the increase in strength from the trained limb to the untrained limb. In a 2006 update, Carroll et al. combined results from 16 cross-education studies and found the untrained limb increased strength 8% on average, which corresponded to half

(52%) of the increase in strength on the trained side. It is now widely accepted that cross-education results in a change in untrained limb strength.

1.2.2 Mechanisms of Cross-education

There have been many proposed mechanisms of cross-education; however, there is currently no consensus that a single mechanism is responsible for the effect. It is possible that there are numerous adaptations that collectively work together to produce the strength increase in the untrained limb. Considering there may be multiple sites of adaptation, the current state of technology may lack sensitivity in measuring the effect (Carroll et al., 2006). The following sections will describe potential mechanisms of cross-education.

1.2.2.1 Muscle Mechanisms

It is widely known that strength training in a trained limb produces adaptations at the peripheral muscle level such as muscle hypertrophy, increased enzyme concentration, and alterations in the composition of contractile proteins (Folland & Williams, 2007). Cross-education not only results in improved strength in the trained limb, but also shows increased strength in the untrained limb. Studies examining physiological changes in the untrained limb have failed to show significant changes at the peripheral muscle level that would lead to the increase in strength. The trained limb has been shown to hypertrophy in cross-education studies; however, the untrained limb has not been shown to increase muscle size (Farthing et al., 2005). Other studies have found no change in fibre type or cross-sectional area in the untrained limb (Moritani & deVries, 1979; Ploutz et al., 1994; Hortobágyi et al., 1996), therefore it is assumed that there is little to no adaptation at the muscle level.

Cross-education may be attributed to muscle activation in the untrained limb during strength training of the trained limb. These have been called “associated contractions” or “mirror activity” (Cincotta & Ziemann, 2008; Sehm et al., 2010). Some studies have shown electromyography (EMG) activity in the untrained limb during strength training (Zijdwind & Kernell, 2001; Farthing et al., 2005). Farthing et al. (2005) measured EMG activity in both the trained and untrained forearms during a typical training set. They found that the training arm was activated 93.8% of peak isometric activation on average, whereas the non-training arm was activated 11.7% on average. Other studies have found no significant muscle activation of the untrained limb (Hortobágyi et al., 1997; Evetovich et al., 2001). Muscle activation of the untrained limb may contribute to cross-education, yet it is difficult to determine if the magnitude of activation is large enough to contribute to the cross-education effect. Mechanomyography (muscle sounds and muscle vibrations) have been found to transfer to the untrained limb after strength training (McKay et al., 2006), providing some support for crossover of muscle mechanisms. Muscle mechanisms are likely not a main contributor to cross-education; however, they should not be ruled out.

1.2.2.2 Spinal Mechanisms

The contribution of spinal mechanisms in conjunction with cortical mechanisms may lead to cross-education. The brain and spinal cord work together very closely in executing movement, which may suggest that there are spinal influences contributing to the increase in strength shown in an untrained limb. Spinal cord mechanisms may contribute to cross-education by modifying reflexes or altering descending commands to the muscle (Pierrot-Deseilligny & Burke, 2005). Hortobágyi et al. (2003) demonstrated a depression in the H-reflex of the flexor carpi radialis by

strong unilateral flexion and extension of the contralateral wrist. Authors suggested that presynaptic inhibition of Ia afferent motoneuron synapses may be responsible for the effect.

Lagerquist et al. (2006) investigated unilateral changes after lower limb strength training on plasticity in the spinal cord in healthy participants. Results showed a significant increase in strength in both trained and untrained limbs after the 5-week training interval, indicating a cross-education effect. There was also a significant increase in spinal reflex excitability in the trained limb; however, no change in H-reflex amplitude in the untrained limb. The authors suggested that spinal and supraspinal changes occurred for the trained limb, whereas only supraspinal changes occurred for the untrained limb. This study proposed that cross-education was not due to spinal mechanisms, and may be due to something higher order.

Recent evidence has since suggested that spinal reflex plasticity plays a role in cross-education (Dragert & Zehr, 2011). Dragert and Zehr (2011) found significant cross-education in the ankle dorsiflexors, and found significant changes in the H-reflex excitability threshold using healthy participants. Participants trained the ankle dorsiflexors for 5-weeks. The authors suggested there was a change in spinal cord excitability due to a generalized descending signal to the lower body impacting both the trained and untrained limbs. This study provides evidence of plastic neural adaptations in spinal reflex output produced by unilateral training. Although Dragert and Zehr (2011) provide preliminary evidence of the contribution of the spinal cord in cross-education, more research should be conducted to further investigate the influence of the spinal cord on cross-education.

1.2.2.3 Cortical Mechanisms

There is evidence that the structure and organization of the brain may play a role in cross-education. Networks of areas in the brain are involved in the planning and initiation of movement (Carroll et al., 2006). These areas are found in the cortex and are organized in a hierarchical manner. Higher order decision making and planning are controlled in the prefrontal regions of the cortex, and direct control of motor neuron output is controlled in the primary motor cortex (Carroll et al., 2006). The areas of the brain are connected by the central white matter, which contains myelinated fibers forming bundles that extend from one cortical region to another. Association fibers interconnect areas of the neural cortex within a single cerebral hemisphere, projection fibers link the cerebrum with other regions of the brain and spinal cord, and commissural fibers connect the two cerebral hemispheres. The two most prominent commissural fibers are the corpus callosum and the anterior commissure. An anatomical connection between the two hemispheres is thought to play a significant role in the transfer of sensory and cognitive information, and in coordinating motor planning and control (Eliassen et al., 1999). It has also been suggested that interneurons may play a significant role transferring information from one side of the primary motor cortex to the other (Hortobaygi, 2005). The connections between the two hemispheres are thought to play a role in cross-education (Lee & Carroll, 2007).

Unilateral strength training of one limb may cause changes in the organization of motor pathways controlling the contralateral muscle (Lee & Carroll, 2007). High force unilateral voluntary contractions alter the excitability of cortical pathways projecting to the opposite side (Hortobaygi et al., 2003; Muellbacher et al., 2000; Dettmers et al., 1995). This may happen by

decreasing transcallosal inhibition between the two sides of the primary motor cortex and by producing long-term alterations in the transcallosal pathways (Lee & Carroll, 2007). Similarly, Carroll et al. (2006) suggested that a strong contraction of one limb can affect the gain of the ipsilateral cortical circuitry. Repeated contractions may induce adaptations in the untrained control system to allow more effective motor drive when the untrained limb is maximally contracted (Carroll et al., 2006), and therefore may produce the cross-education effect. This may be due to connections between the two sides of the primary motor cortex (Di Lazzaro et al., 1999; Hanajima et al., 2001) and possibly due to connections from the pre-motor cortex to the primary motor cortex (Mochizuki et al., 2004).

Strength training of one limb can theoretically cause adaptations between cortical areas other than the primary motor cortex. Callosal connections between the bilateral supplementary motor areas, cingulate motor areas, and prefrontal areas may be where additional adaptations occur (Iwamura et al., 2001). It has been shown in imaging research that these areas are activated in unilateral contractions (Dettmers et al., 1996). Neuroimaging research should be conducted to assess functional reorganization after unilateral strength training; however, there are limitations to using these imaging techniques. Imaging cannot usually differentiate between excitatory or inhibitory activation, or distinguish if changes in cortical activity involve input or output (Carroll et al., 2006).

A study by Farthing et al. (2007) examined changes in brain activity via functional magnetic resonance imaging (fMRI) after unilateral strength training of the dominant (right) hand. When using fMRI, a region of the brain that demonstrates more activation is considered to be more physiologically active. Functional magnetic resonance imaging can show changes in cortical activity by detecting an increase in the amount of oxygenated blood in a cortical region

(Farthing, 2009). Results of the Farthing et al. (2007) study showed that for the right (trained) hand, there were changes in activation in both cortical hemispheres and evidence of an increase in activation of the contralateral sensorimotor cortex. For the left (untrained) hand there was an increase in activation in the contralateral sensorimotor cortex and ipsilateral temporal lobe regions. The temporal lobe is normally involved in retrieval of motion knowledge and semantic memory (Farthing, 2009). The new activation in the temporal lobe that Farthing et al. (2007) found as a result of unilateral strength training may indicate memory retrieval of the strength task. Better memory retrieval of a task may assist in motor planning and execution, and in turn may result in the increase in strength shown in cross-education. This study suggests that there is a change in neural activity that may be shared between the hemispheres (Farthing et al., 2007).

More recently, there has been additional evidence of cortical adaptations to cross-education. Lee et al. (2009) showed that unilateral strength training increased cortical drive from the motor cortex to the untrained muscles using transcranial magnetic stimulation (TMS). TMS is a non-invasive procedure that stimulates the primary motor cortex using a magnetic pulse. The stimulation produces a motor evoked potential (MEP). The peak-to-peak amplitude of the MEP represents the number of descending synapses to the target muscle, known as cortical excitability (Hallett, 2000). In 2010, Lee et al. found increased corticospinal excitability in both the contralateral and ipsilateral hemisphere after performing a ballistic finger abduction task. Hortobágyi et al. (2011) greatly advanced the literature on neural mechanisms to cross-education after finding decreased interhemispheric inhibition during activity in the untrained limb. The study used TMS to assess healthy volunteers who trained the first dorsal interosseus. Results showed a 49.9% increase in strength in the trained limb, and a 28.1% increase in strength in the untrained limb. Hortobágyi et al. (2011) is the first study to show evidence for plasticity of

interhemispheric connections to mediate cross-education produced by a simple motor task.

Latella et al. (2012) also used TMS after 8 weeks of unilateral leg strength training to show there was decreased inhibition to the motoneuron pool, which is thought to contribute to an overall net excitability of the corticospinal pathway. These studies provide further support for a cortical mechanism to cross-education.

Two studies have investigated cortical adaptations following unilateral limb immobilization in healthy (i.e. non-injured) participants (Farthing et al., 2011; Pearce et al., 2012). Farthing et al. (2011) immobilized the non-dominant (left) limb using a forearm cast, while the non-immobilized (right) limb strength trained with isometric handgrip contractions 5 days per week. A second group also had their non-dominant (left) limb immobilized, but conducted no strength training. Cortical activation was measured before and after strength training using fMRI. There was a maintenance of strength in the immobilized limb of the training group, and a decrease in strength of the immobilized limb in the non-strength training group. The maintenance of strength for the training group was associated with increased volume of activation in the contralateral motor cortex, whereas the non-training group showed no changes in contralateral motor cortex activation. Pearce et al. (2012) used a sling immobilization model and TMS to assess cortical activation. The study supported the findings of Farthing et al. (2011) by showing a maintenance of strength of the immobilized limb of the training group, and a decrease in strength of the immobilized limb in the non-strength training group. Pearce et al. (2012) also showed that the maintenance in strength was associated with a maintenance of corticospinal excitability for the immobilized arm of the training group, whereas the immobilized arm of the non-strength training group showed a decrease in corticospinal excitability. The

results of these two studies provide evidence of a cortical mechanism for cross-education after immobilizing a healthy (non-injured) limb.

1.2.2.4 Enhanced Drive to the Muscles

Another factor that may influence the cross-education effect is alterations in neural drive to the muscles. Neural drive may be increased to agonist and synergist muscles, and may be decreased to antagonist muscles in an untrained limb, which could account for increases in strength (Carroll et al., 2006). Two factors that may contribute to these alterations in neural drive are the effects of Ia afferents and Renshaw cells. Ia afferents are responsible for inducing inhibition on the motor neuron connecting to the antagonist muscle in a muscle contraction (Lee & Carroll, 2007). This process is referred to as reciprocal inhibition. Renshaw cells are a type of interneuron that also produces inhibition. They create inhibition by spreading over the motoneuron pool and by innervating synergist muscles. Renshaw cells also receive input from the brain, which can act as a control mechanism for movement (Latash, 2008). Adaptations to neural drive in both Ia afferents and Renshaw cells may have potential to generate additional force (Lee & Carroll, 2007), and in turn may mediate cross-education by increasing force production in an untrained limb.

Strength training can increase peak firing rates and doublet firing at the onset of muscle contraction (Van Cutsem et al., 1998), along with modifications in motor unit synchronization (Milner-Brown et al., 1975; Semmler & Nordstrom, 1998). These types of changes may alter the pattern of neural activity associated with motor output and execution of a task, and may in turn contribute to cross-education (Carroll et al., 2006). The neural adaptations involved in strength

training may parallel the mechanisms that occur in cross-education; however, these adaptations remain unclear.

1.2.2.5 Motor Learning

In motor learning, there is a bilateral transfer of skill (i.e. practicing a motor task on one limb will improve performance of the same task when executed in the opposite limb) (Lee & Carroll, 2007). There may be a complete, partial or asymmetrical transfer depending on the task (Lee & Carroll, 2007). Asymmetrical transfer refers to unidirectional transfer of learning, either from the dominant to non-dominant side, or non-dominant to dominant side (Parlow & Kinsbourne, 1990). It has been suggested that strength training is a form of motor learning (Lee & Carroll, 2007). As previously mentioned, cross-education has been shown to transfer on average 52% of the strength gained in the training limb (Carroll et al., 2006), resulting in partial transfer of strength. Farthing et al. (2005) has also found that cross-education is asymmetrical (cross-education effects were evident when the dominant hand strength trained, however effects were not significant when the non-dominant hand conducted the training). If strength training is considered a motor learning activity, then a mechanism of cross-education may be through motor learning. This may occur by the creation of a neural circuit that executes the task to produce maximal output from muscles. Once this circuit is created, it may be stored and accessed by both sides of the brain, which may contribute to an increase in force in the untrained limb (Lee & Carroll, 2007).

Farthing (2009) created a model describing the effects of motor learning on cross-education. The model is formed from the hypothesis that cross-education of strength is similar to cross-education of skills, and that they are both predominantly controlled by cortical mechanisms.

The model is based on three levels where adaptation could contribute to the force output of the limb: the motor planning level, motor command level, and peripheral muscle level. It illustrates that if there is a greater ability by the dominant limb system at any of the three levels, there will be a greater increase in strength (Farthing, 2009). The dominant limb is likely to be more capable before training; therefore, will become more capable with training, therefore, it is more likely to master the task. Once the task is mastered, goals of the movement, and patterns of muscle activation may be transferred to the non-dominant limb to enhance motor planning and motor commands. This will result in cross-education of strength (Farthing, 2009). At the end of the strength training period in the dominant limb, both limbs will be equivalent at the motor planning level. At the motor command level, both limbs will show enhanced strength; however, the training limb will still be able to execute the task better than the non-training limb due to the improved motor pathways during the training. At the peripheral muscle level, the training limb will have increased muscle size due to the training, resulting in greater strength for the trained limb. The contralateral untrained limb will not show changes at the muscle level; however, the increased strength will be a result of nervous system adaptation (Farthing, 2009).

Farthing (2009) provides a practical model of cross-education, demonstrating the effects of motor planning, motor output, and peripheral muscles. Although this model can help explain cross-education, it is important to note that it is designed for the upper extremity only. There has been little research conducted on the lower limbs, therefore the lower extremities may have a different mechanism of cross-education adaptation.

There are many proposed mechanisms of cross-education, with the evidence pointing towards one that is cortical in nature. There may not be one single mechanism that contributes to cross-education, but a combination that work together to produce the effects in the untrained

limb. More research is needed to determine what these mechanisms are, and how they may be used when applying cross-education to unilateral immobilization models, or to rehabilitation settings.

1.2.3 Effects of Cross-education

It is widely known that strength training results in trained limb increases in muscle strength and muscle size, which help to improve functional ability. There are also changes in the trained limb such as increased enzyme concentration, and alterations in the composition of contractile proteins (Folland & Williams, 2007). When unilaterally strength training one limb, as in cross-education models, the trained limb behaves the same as in a normal strength training intervention. The untrained limb also increases strength; however, there are no increases in muscle size and no changes in fibre type or cross-sectional area (Moritani & deVries, 1979; Ploutz et al., 1994; Hortobágyi et al., 1996). Cross-education is usually shown in studies when the training duration lasts 4-12 weeks (Zhou, 2000). The phenomenon is believed to be neural in nature due to the rapid increases in strength in a relatively short period of time. In addition, there is normally hypertrophy of the trained limb, and no hypertrophy of the untrained limb, even though the untrained limb's relative increase in strength may exceed the trained limb's strength increase (Farthing et al., 2005).

1.2.3.1 Characteristics of the Effect

Cross-education is not specific to certain muscle groups (i.e. only the upper body). It occurs in both the upper and lower body (using large muscle groups of the quadriceps, to very small muscle groups of the intrinsic hand) (Yue & Cole, 1992; Evetovich et al., 2001; Farthing et

al., 2005; 2009). Cross-education is also not specific to certain ages or sexes. Effects have been shown in both young and old adults, and in both males and females (Zhou, 2000).

Previously, it has been accepted that cross-education occurs from homologous to homologous muscle (Zhou, 2000) (i.e. if the biceps brachii is trained on the right side, the biceps brachii on the left side will see an increase in strength via cross-education). Hortobágyi et al. (1999) determined that 6 weeks of knee extension training increased strength in both the trained and untrained knee extensors, but found no increase in handgrip strength. However, more recent research suggests that both the agonist and antagonist muscles surrounding the homologous joint could be affected by cross-education (Sariyildiz et al., 2011). Sariyildiz et al. (2011) examined whether unilateral strength training would increase strength in the opposite untrained agonist and antagonist muscles. The study used electrical muscle stimulation training on the wrist flexors to determine if the wrist extensors would increase strength. The trained limb wrist flexors increased strength by 50%, and the untrained limb wrist flexors increased strength by 44%. The untrained limb wrist extensors (i.e. the antagonist muscle) also increased strength by 46%, demonstrating that cross-education was not confined to the homologous muscle. The results suggest cross-education may also influence the antagonist muscles of the homologous joint that would be involved in a strength movement in opposition to the training task. More research should be done to further investigate the transfer to surrounding muscles.

Cross-education preferentially occurs from the dominant to non-dominant limb. Farthing et al. (2005) investigated the direction of transfer using young, healthy right-handed participants. Participant's strength trained either their dominant (right) hand, or their non-dominant (left) hand using isometric ulnar deviation. Cross-education occurred when the right-hand was the training

limb (39% transfer in strength); however, no significant effects were found when the left-hand was the training limb (9% transfer in strength).

The majority of cross-education literature does not report limb dominance, which may be the reason for the variation in the transfer of strength (Farthing, 2009). Farthing (2009) compared the cross-education effect of studies that reported limb dominance and trained the upper body. The largest transfer came from studies that trained their dominant limb in right-handed participants. The increase in strength in the untrained limb was on average 32%, with the transfer from the trained limb ranging from 63% to 150%. This can be compared to the most recent meta-analysis conducted by Carroll et al. (2006) who did not account for limb dominance and found the strength increase of the untrained limb to be 8%, and 52% of the trained limb's increase in strength. Of the studies that Farthing (2009) compared, most studies that reported left-limb training and non-dominant limb training did not show significant cross-education. There is limited research available to determine if the dominant to non-dominant transfer is consistent in left-handed individuals, or if the dominant to non-dominant transfer is consistent in the lower body. Cross-education studies that have targeted the lower limbs have not identified whether participants were right or left-footed, and most studies trained the left leg, as was determined by kicking preference (Farthing, 2009). The transfer of strength in the lower limbs is quite variable (Hortobágyi et al., 1997), which also may be influenced by limb dominance. More research needs to be conducted to determine transfer effects in the lower body and in left-handed individuals.

1.2.3.2 Novel Training Tasks and Cross-education

Cross-education effects are larger when using more novel or more unfamiliar tasks. Unique tasks such as ulnar deviation (i.e. movement of the wrist in a forward and downward direction) have been used to maximize the cross-education effect (Farthing et al., 2005). Farthing (2009) suggested that the characteristics of the strength task might influence the magnitude of cross-education. A more novel task is likely to have a greater strength asymmetry between the dominant and non-dominant limb prior to any strength training, whereas a simple task such as handgrip is more likely to be similar between limbs (Steenhuis, 1999). The degree of strength asymmetry between limbs is likely dependent on factors such as how skilled or complex the task is (Steenhuis, 1999), and how novel it is to the individual completing the task (Farthing, 2009). These factors likely contribute to the amount of motor learning that takes place when performing the skill. Farthing et al. (2005) suggested that a more complex task would have a larger motor learning component, compared to a simple skill whereby small motor learning would take place. Furthermore, the more complex skill with large motor learning would transfer better from the dominant to non-dominant limb and show a larger cross-education effect (Farthing et al., 2005).

Cross-education has been shown to occur when using imagined contractions (Yue & Cole, 1992). Yue and Cole (1992) investigated if cross-education could be facilitated in voluntary contractions versus imagined contractions of the untrained hand after 4-weeks of training. The trained hand of the voluntary training group increased strength 30%, whereas the trained hand of the imagined group increased strength 22%. In the untrained limb, the training group showed a significant cross-education effect of 14%, whereas the imagined group showed a significant cross-education effect of 10%. This demonstrated that strength could increase in both the trained

and untrained limbs without voluntarily contracting the muscles. In contrast, Farthing et al. (2007) conducted imagery training on participants who completed imagined contractions with the task of ulnar deviation. The imagery training group had no increase in strength for either the training arm, or the non-training arm. Other research has been conducted to investigate the effects of imagined contractions, but has not looked at the effect in the untrained limb (Ranganathan et al., 2004). Ranganathan et al. (2004) found that imagined contractions increased strength in the trained limb for both finger abduction and elbow flexion. More research should be conducted to determine if cross-education training effects can be replicated using imagined contractions.

1.2.3.3 Impact of the Training Program on Cross-education

The intensity of training to produce cross-education normally occurs when the participant is producing force greater than 60% of their maximal voluntary contraction (Zhou, 2000). Cross-education strength training also has the greatest effects when the testing mode is specific to the type of training that was used in the trained limb (Zhou, 2000). Hortobágyi et al. (1997) unilaterally trained participants both eccentrically and concentrically, and evaluated eccentric, concentric, and isometric strength on both limbs after a 12-week training program. When tested concentrically, the concentric training group had a 30% transfer in strength to the untrained limb, whereas the eccentric group had an 18% transfer in strength. Conversely, when tested eccentrically, the eccentric group had a 77% increase in strength in the untrained limb, whereas the concentric group had a 10% increase in strength. This demonstrates the specificity of training to testing for the cross-education effect.

Unilateral isometric, eccentric, and concentric strength training have all shown significant strength increases to the untrained limb (Hortobágyi et al., 1997; Farthing et al., 2003; Farthing et al., 2011); however, the type of voluntary contraction with the greatest transfer of cross-education is eccentric contractions. Hortobágyi et al. (1997) found a strength transfer of 77% when participants trained eccentrically, and a transfer of 30% when trained concentrically. In a study investigating if the velocity of eccentric contractions was specific to the transfer, it was found that fast velocity eccentric contractions (180° per second) had significant cross-education effects, whereas slow velocity eccentric contractions (30° per second) had no significant transfer of strength to the untrained limb (Farthing & Chilibeck, 2003).

Electrically evoked eccentric contractions seem to have the best overall cross-education effect (Zhou, 2000). Hortobágyi et al. (1999) found that participants who trained unilaterally using electrically evoked eccentric contractions had a greater increase in strength to the untrained limb (104%) compared to participants who trained using voluntary eccentric contractions (34%). Similarly, Sariyildiz et al. (2011) found large strength increases (50% in the trained limb, and 44% in the untrained limb) in electrically evoked eccentric contractions on the wrist flexors. The large increase in strength may be due to the additive effect of electrically evoked contractions and muscle lengthening (Hortobágyi et al., 1999).

1.2.4 Application of Cross-Education to Healthy Immobilization Models and Clinical Settings

A large gap in the literature remains in applying cross-education to clinical rehabilitation settings. There is obvious therapeutic potential to use cross-education in unilateral injuries; however, very few studies have attempted to apply cross-education to unilateral limb

immobilization. Stromberg (1986; 1988) (reports from the same data set) has conducted the only study to date that has applied cross-education to a rehabilitation setting using participants with various upper extremity injuries (i.e. carpal tunnel, collateral ligament repair, digital nerve repair). The study investigated the effects of cross-education on twenty patients (10 per group) after three weeks of immobilization in a splint. After the surgery, patients were given an at-home exercise program for the contralateral healthy extremity and were instructed to refrain from exercise in the operated extremity. The study found that individuals with wrist/forearm injuries who strength trained the non-injured limb showed improved function (i.e. strength and ROM) in the injured limb compared to a non-training group. Stromberg stated that there was a large increase in strength (~50%) in the operated extremity of the training group, and a consistent increase in range of motion, with the effects maintained for up to three months. Although this study looks as though it has promising results, there are many limitations, which may invalidate the findings. Large baseline differences were unaccounted for, the study did not report the type strength training program that was used, and raw data were not included in the paper making it difficult to draw any conclusions.

Farthing et al. (2009) was the first study to apply cross-education to a unilateral immobilization model using healthy (i.e. non-injured) participants. The study randomized thirty participants into one of three groups. Two groups casted their non-dominant (left) forearms for 3 weeks. One of the immobilized groups strength trained their non-immobilized (right) arm during the immobilization period, and the other group conducted no strength training. The third group served as a control with no immobilization and no strength training. Results showed that the training arm of the training group had a 23.8% increase in strength, and the immobilized arm of the training group had no significant change in strength (2.2%). For the group that was

immobilized and conducted no strength training, the non-immobilized arm had no significant change in strength, and the immobilized arm had a 14.7% decrease in strength. The study also monitored changes in muscle size and found that the immobilized arm of the training group had no significant change in muscle size (-1.1%), whereas the non-training group had a 4.3% decrease in muscle size. This was the first study to show that decreases in muscle strength and muscle size can be attenuated in an immobilized limb by strength training the non-immobilized limb in healthy (i.e. non-injured) participants.

The finding of an attenuation of strength loss in the immobilized limb of the training group was replicated by Farthing et al. (2011) using the same forearm casting model; however, both immobilization groups showed a decreased in muscle size, with no difference between groups. Farthing et al. (2011) did not speculate why there was no maintenance in muscle size, which warrants further investigation. In 2010, Magnus et al. (published as Study 1 in thesis) used the same study design as Farthing et al. (2009), but applied the immobilization to a shoulder unloading model. Twenty-five young, healthy participants wore a shoulder sling and swathe for 4-weeks and the training group strength trained the non-immobilized arm during the immobilization period. Strength training the non-immobilized limb provided a benefit for both strength and muscle thickness in the immobilized limb. These findings were later supported by Pearce et al. (2012) who used the methods of Magnus et al. (2010) and Farthing et al. (2011) to determine that strength training of the non-immobilized limb helped maintain strength and muscle thickness of the immobilized limb after 3-weeks of wearing a shoulder sling. The results of these model immobilization studies are very novel, demonstrating that cross-education is beneficial for attenuating the loss of muscle strength and muscle size in an immobilized healthy limb while strength training the opposite limb.

The findings from Farthing et al. (2009; 2011), Magnus et al. (2010), and Pearce et al. (2012) demonstrate beneficial effects in the application of cross-education to unilateral limb immobilization in healthy (i.e. non-injured) participants. When applying cross-education to real injury settings, a maintenance in strength and muscle size of the injured limb is not expected. Immobilization of a limb has many negative effects on muscle, including modifications in contractility (Duchateau & Hainaut, 1987), declines in electromyographic (EMG) activity (Deschenes et al., 2002; Parcell et al., 2000) and maximal voluntary muscle activation (Vanderborne et al., 1998; Gondin et al., 2004). Strength decreases up to 60% after 5-6 weeks of immobilization following injury (Fuglsang-Fredriksen & Schell, 1978; Witerstad-Lossing et al., 1988). Instead of finding a maintenance in strength and muscle size as in cross-education model immobilization studies, there would likely be less of a loss in muscle strength and muscle size than what would normally be shown after an injury.

There have been no cross-education studies to date that have investigated the effect of cross-education on functional outcome (i.e. AROM, self-rated function). The literature has focused outcome measures on strength and muscle adaptations (i.e. EMG and muscle size); therefore it is unknown if cross-education can improve functional outcome. This is particularly important when applying cross-education to an injury setting, whereby outcome measures would likely not only include strength tests, but would also include measures such as AROM and self-rated function to determine clinical significance. There is currently no evidence to suggest that cross-education would improve AROM; however, AROM may be viewed as an indirect measure of strength due to the muscles moving the joint through the range, versus passive ROM where the muscles are not actively involved in moving the joint. If AROM is considered an indirect measure of strength, it may improve following cross-education training. There is also no

evidence to suggest that cross-education would improve self-reported function (i.e. activities of daily living); however, it could be argued that the stronger an individual is, the easier it may be to perform daily tasks. Studies need to be conducted to determine if cross-education can benefit an injured limb, and to what extent it may improve the overall rehabilitation (i.e. strength, AROM, and self-rated function) after a unilateral injury. If cross-education can improve outcome after unilateral injuries, rehabilitation strategies could be changed to incorporate unilateral strength training of the non-injured limb.

1.2.5 Statement of the Problem

There is great potential for the application of cross-education to unilateral injury settings. Farthing et al. (2009; 2011) showed promising results using a model of forearm casting to apply cross-education to non-injured participants. The two Farthing studies represent the only cross-education and model immobilization research studies (prior to the thesis). The forearm casting model well represented a real injury since participants remained immobilized throughout the full duration of the study. However, one limitation was that muscle activation could not be monitored in the immobilized limb during training sessions since the cast could not be easily removed and replaced. Further investigation is warranted for a different model of immobilization that could monitor muscle activation and determine if the results of Farthing et al. (2009; 2011) could be replicated in an immobilization setting other than forearm casting.

Shoulder slinging represents a good model for the application of cross-education since it allows easy access to the muscles during the immobilization period, whereby muscle activation could be measured. Further, cross-education could conveniently be applied to shoulder injuries in a clinical setting since rotator cuff pathology is one of the most common types of upper

extremity injuries (Herberts et al., 1984), and typically results in surgery followed by immobilization in a sling. Although surgery has been shown to improve the condition (Kirschenbaum et al., 1993; Rokito et al., 1996; Cools et al., 2006; Holtby and Razmjou, 2010); evidence suggests that there are strength deficits ranging from 15 – 36% up to 6-8 months after the surgery (Binet et al., 2003), and satisfactory results after 1 year of rehabilitation (Rokito, 1999). Even after an average of 5 years post-surgery, a decline in strength still remains when compared to the non-operated extremity (Rokito, 1999). The standard rehabilitation protocol after shoulder surgery is immobilization in a sling, followed by the introduction of ROM exercises and basic strength restoration (Millett et al., 2006; Conti et al., 2009). Current rehabilitation programs for shoulder injuries do not provide formalized strength training on the non-surgical side after surgery (Millett et al., 2006; Conti et al., 2009). The implementation of a strength training program on the non-surgical limb after surgery may improve the rehabilitation of the surgical limb via cross-education.

Another model to investigate cross-education in clinical settings, as a natural extension of previous work, is wrist fractures. The cross-education model immobilization studies with forearm casting have already been completed by Farthing et al. (2009; 2011) and showed promising results. Distal radius fractures are one of the most common types of fracture (Larsen & Lauritsen, 1993), especially in older women (Handoll et al., 2006). The rehabilitation after a distal radius fracture is quite slow, and it can often be difficult for individuals to return to their normal level of functioning. The rehabilitation typically consists of forearm casting for 6 weeks, followed by active and passive ROM exercises, and strengthening focused on the fractured limb. Brogren et al. (2011) showed that 1-year post fracture grip strength was 88% of the non-fractured limb, with participants continuing to improve grip strength, pain and ROM up to 2-4 years post-

fracture. Self-reported function (via the Patient Rated Wrist Evaluation (PRWE)) is also not typically recovered at 6 months post-fracture (MacDermid et al., 2002; Maciel et al., 2005). There is currently no clear evidence of the best rehabilitation protocols following wrist fractures (Handoll et al., 2006); and cross-education has not been addressed as a potential rehabilitation strategy.

There is a clearly a large gap in the literature in applying cross-education to injuries; therefore the first three studies in this document aimed to investigate if cross-education could improve strength and functional outcome of the immobilized limb after shoulder immobilization. The purpose of the first study was to apply cross-education during 4-weeks of unilateral limb immobilization using a shoulder sling and swathe to investigate the effects on muscle strength, muscle size, and muscle activation. The purpose of the second study was to determine if an at-home resistance tubing strength training program of one shoulder (that is commonly used in rehabilitation settings) could produce increases in strength in the trained and untrained shoulders via cross-education. The purpose of the third experiment was to apply the clinically relevant shoulder strength training program (used in study 2) to unilateral shoulder surgery participants, and determine if cross-education training could improve strength, muscle size, AROM, and self-reported function of the surgical limb. The purpose of the last experiment was to apply cross-education to unilateral distal radius fracture participants, and evaluate the effects on muscle strength, AROM, and self-reported function.

1.2.6 Hypothesis

1.2.6.1 Experiment 1

Cross-education strength training would result in a maintenance in strength, muscle size, and muscle activation of the immobilized limb in the strength training group compared to the non-trained group who would have a decrease in strength, muscle size and muscle activation in the immobilized limb.

1.2.6.2 Experiment 2

The at-home resistance tubing unilateral shoulder strength training program would significantly increase strength in both the trained and untrained limbs of the training group compared to the non-training group, exhibiting effects in similar magnitude to previous cross-education studies (i.e. 52% transfer to the untrained limb).

Muscle size would increase in the trained arm of the training group, and the non-trained arm of the training group would show no change in muscle size.

1.2.6.3 Experiment 3

Strength training of the non-surgical limb in addition to standard rehabilitation of the surgical limb would result in improved strength, AROM, muscle size and self-reported function when compared to normal rehabilitation alone after unilateral shoulder surgery.

1.2.6.4 Experiment 4

Strength training of the non-fractured limb in addition to standard rehabilitation of the fractured limb would result in improved strength, AROM and self-reported function when compared to normal rehabilitation alone after a unilateral distal radius fracture.

Chapter 2: Experiment 1

Experiment 1 has been published in a peer-reviewed exercise physiology journal (Magnus et al., 2010, Title: Effects of cross-education on the muscle after a period of unilateral limb immobilization using a shoulder sling and swathe). It is presented in its published form with the exception of some minor changes necessary for the conversion to graduate thesis format.

2.1 Introduction

Immobilization or unloading of a limb can have many effects on muscle. Immobilization places the limb in a passive state (Yue et al., 1997), generates modifications in contractility (Duchateau & Hainaut, 1987), decreases electromyographic (EMG) activity (Deschenes et al., 2002; Parcell et al., 2000) and maximal voluntary muscle activation (Duchateau & Hainaut, 1987; Vanderborne et al., 1998; Gondin et al., 2004). Significant declines in muscle strength have been shown in the affected limb following immobilization (Hortobágyi et al., 2000; Parcell et al., 2000; Deschenes et al., 2002; Gondin et al., 2004; Miles et al., 2005). Strength has been shown to decrease up to 60% after 5-6 weeks of immobilization following injury (Fuglsang-Fredriksen & Schell, 1978; Witerstad-Lossing et al., 1988). The majority of muscle strength is lost within the first 2 weeks of disuse (Vanderborne et al., 1998), suggesting that this early decline in strength is due to neural mechanisms (Deschenes et al., 2002).

Evidence is mixed as to whether short duration immobilization leads to a decrease in muscle size. Decreases in muscle size of 4.0% after 4 weeks of immobilization (Parcell et al., 2000), 7.7% after 3 weeks of immobilization (Miles et al., 2005), and 11.8% after 10 days immobilization (Thom et al., 2001) have been shown. Conversely, other studies have found no

change in muscle size after 2 weeks (Deschenes et al., 2002) and 3 weeks (Kitahara et al., 2003) of immobilization.

It is important to discover new ways of minimizing changes in the muscle for quicker recovery from any injury. One way of minimizing this decline may be to apply cross-education to a period of disuse. Cross-education of strength is defined as the increase in strength of the untrained contralateral limb after unilateral training the opposite homologous limb (Carroll et al., 2006; Farthing et al., 2005). The exact mechanisms of cross-education are not known; however, the current literature suggests the mechanisms are neural (Carroll et al., 2006; Lagerquist et al., 2006; Farthing et al., 2009). In cross-education, the increase in strength of the untrained limb is thought to be related to the gain in magnitude of the trained limb, and is on average 52% of the strength gain observed in the trained muscle (Carroll et al., 2006). Greater transfer to the untrained limb has been demonstrated in more novel or unfamiliar tasks (Farthing et al., 2005). The cross-education effect has been consistently shown after unilateral training in healthy individuals; however, less is known about the effect of cross-education in a disuse setting.

Farthing et al. (2009) recently conducted a study that applied cross-education to a healthy immobilized limb. The study showed that strength training the free limb via ulnar deviation attenuated the loss in muscle strength and size in the immobilized limb during a 3-week period of unilateral forearm casting. This study demonstrates clear evidence to suggest that strength training the free limb provides a maintenance effect for the immobilized limb; however, only the primary agonist muscle was investigated, and only one exercise for strength training was used. In a clinical setting it is unlikely that one exercise would be used for rehabilitation from an injury, therefore making it difficult to generalize these results. More evidence is needed to determine if

cross-education can be used in a clinical setting and if it can be applied to different types of immobilization.

The purpose of the present study was to apply cross-education during 4-weeks of unilateral limb immobilization to investigate the effects on muscle strength, muscle size, and muscle activation. The novel aspect of this study was to use a sling and swathe unilateral unloading model with and without concurrent unilateral training of both the elbow flexors and extensors. To our knowledge, this is the first cross-education study to investigate the effects on the contralateral limb with two different, opposing strength training exercises (i.e. elbow flexion and elbow extension). The sling and swathe unloading model is clinically relevant as many shoulder injuries result in slinging. The sling and swathe model also enabled examination of the effect of immobilization on flexor and extensor muscles, while allowing convenient access to the target muscles during the intervention. The present study also investigated muscle activation in the immobilized limb during strength training sessions of the training limb. This study may help shed light on new approaches to rehabilitation after unilateral injury, whereby strength training the non-affected limb may have beneficial effects on the affected limb (such as during recovery from shoulder surgery where a sling and swathe unloading protocol is commonly used).

2.2 Methods

2.2.1 Participants

Twenty-five healthy males and females from the University of Saskatchewan participated in the study. Prior to commencement, all participants signed informed written consent approved by the biomedical ethics review board at the University of Saskatchewan (see Appendix A for Certificate of Approval). Participants were right-handed according to the Waterloo Handedness

Questionnaire (WHQ). The WHQ 10-item version is scored from -20 to +20 where negative scores indicated left-handedness and positive scores indicated right-handedness. Right-handed participants were chosen to ensure consistency with previous cross-education studies conducted in our lab (Farthing et al., 2005; Farthing et al., 2007; Farthing et al., 2009). All participants were required to refrain from upper body strength training outside the study and to maintain their normal daily routines. Participants reported no recent history of upper limb injuries. Participant descriptive statistics are shown in Table 2.1.

2.2.2 Design

The design of the study was a between-within (mixed) design. The dependent measures were isometric strength, muscle thickness, maximal voluntary activation (interpolated twitch) and electromyography (EMG) in right and left arms. All participants performed a pre-baseline testing session to become familiar with the protocols and to limit any learning of the testing procedures, followed by a baseline testing session 1-week later. Post-testing was completed 4 weeks after baseline. Participants were divided into three groups: the first group, Immobilization+train (Immob+train) (n=8; 2 males, 6 females) wore a sling and swathe and concurrently strength trained their free (right) arm, the second group (n=8; 2 males, 6 females) wore a sling and swathe and did not strength train (Immob), and the third group (n=9; 4 males, 5 females) received no treatment (Control). The sling and swathe was applied to the non-dominant (left) arm in both immobilization groups.

Table 2.1. Participant descriptive statistics for each experimental group. Values are means (\pm SD).

	Immob+Train (n=8)	Immob (n=8)	Control (n=9)
Height, cm	171.7 (9.6)	170.6 (10.3)	175.3 (6.2)
Weight, kg	72.5 (18.3)	83.2 (28.4)	71.6 (11.8)
Age, yr	20.9 (3.2)	20.3 (1.8)*	24.9 (5.1)
Resistance Training Experience, mo	2.8 (4.0)	2.0 (3.9)	5.4 (5.2)
Handedness Score, WHQ	+14.1 (3.6)	+15.4 (5.0)	+16.2 (3.3)
Days Sling Worn	26.0 (2.7)	27.8 (2.3)	-
Hours/Day Sling Worn	13.4 (1.4)	12.6 (0.9)	-

* Age (yr) significantly different between Immob and Control ($P < 0.05$).

2.2.3 Strength Testing and Training

Maximal isometric strength was assessed on both arms for elbow flexion and extension with the elbow joint at a 90° angle. Isometric strength tests were performed on a dynamometer (Humac Norm, CSMi, Stoughton, MA). The highest torque of four repetitions was used for comparisons. Each attempt was maximal and lasted 3 seconds with one minute rest between each contraction. Elbow flexion was tested first followed by elbow extension in the same arm. The arm tested first (right or left) was random with the order kept consistent for all testing sessions. The participants were in a seated position with the chair back angle at 60° and were instructed to keep their opposite arm on their lap. For both elbow flexion and extension contractions, a plastic moulded wrist brace was worn to limit synergist activity of the forearm muscles by eliminating the need for participants to grasp a handle to execute elbow flexion or extension. In elbow flexion contractions, the forearm/wrist of the participant was strapped to a firmly padded arm attachment that was fastened to the dynamometer handle, and the participant pulled on the apparatus to perform the contraction (Figure 2.1). The elbow extension contractions were similarly conducted but with the hand in neutral position and the ulnar aspect of the wrist strapped to the padded arm attachment where the participant pushed on the apparatus to perform the contraction. The same verbal encouragement was given for all testing contractions. At post-testing, strength was assessed 59.3 (SD 15.4) minutes (average of Immob+train and Immob) after removal of the sling and swathe.

All strength training sessions were performed on the Humac Norm dynamometer using the free (right) arm in Immob+train only. The training setup was the same as the testing setup with all training session completed under supervision. Strength training was isometric elbow flexion and extension training 3 times per week for 4 weeks using a progressive protocol.

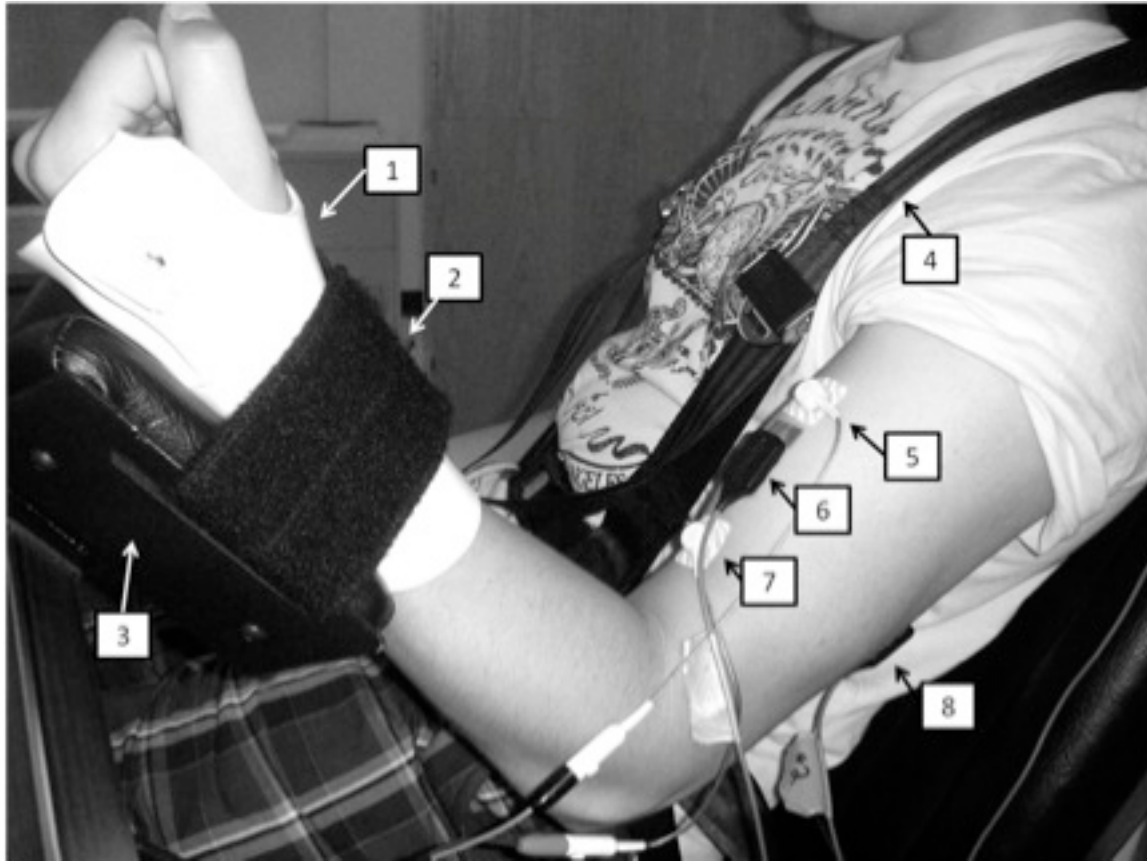


Figure 2.1 Experimental setup for elbow flexion. 1. Wrist brace; 2. Wrist strap; 3. Padded arm attachment; 4. Shoulder stabilization strap; 5. Interpolated twitch electrode (cathode); 6. Biceps brachii electromyography electrode; 7. Interpolated twitch electrode (anode); 8. Triceps brachii electromyography electrode. Note that elbow extension was similarly conducted but with the hand in neutral position (ulnar aspect of the wrist strapped to the padded arm attachment) and the interpolated twitch electrodes were located on the triceps brachii.

Participants began with 3 sets of 8 elbow flexion contractions and 3 sets of 8 elbow extension contractions and progressed each training day by one set until full volume of 6 sets of 8 contractions. During the last two training sessions the volume was reduced to 3 sets to serve as a taper. The training intensity was maximal effort on each repetition, with contractions held for three seconds alternated with three seconds rest. There was one minute rest between each set. Participants were permitted to view their real-time torque and were given verbal encouragement throughout the training.

2.2.4 Muscle Thickness

Muscle thickness was measured using B-mode ultrasound (Aloka SSD-500, Tokyo, Japan), which has been demonstrated to be valid and reliable on previous occasions in our lab (Farthing & Chilibeck, 2003; Farthing et al., 2005; Candow et al., 2006; Krentz et al., 2008). The biceps brachii and triceps brachii were assessed prior to any strength testing. Both arms were measured with a stringent landmarking method using an overhead transparency film to ensure identical locations at all testing time points (Farthing & Chilibeck, 2003). Biceps brachii and triceps brachii muscle thickness were measured on the bulk of the muscle when it was in a lengthened position. The ultrasound probe was placed at the centre of the muscle bulk. The right arm was always measured first to ensure standardized timing of the procedure. At each testing point, four measurements were taken on each arm with the average of the two closest measures used as the thickness value. Additional measurements were taken in the event that any two of the four measurements were not within 1 mm to ensure precision.

2.2.5 Interpolated Twitch

A Digitimer Constant Current High Voltage Stimulator (Model DS7AH) was used to activate the elbow flexors and extensors. Self-adhesive electrodes were used with the cathode placed over the proximal muscle belly in both the biceps brachii and triceps brachii and the anode placed over the distal tendon of the biceps and triceps brachii (Figure 2.1). Two doublet pulses (at 100Hz, 50 μ s pulse duration) were applied, both during and approximately 5 seconds after the maximal voluntary contraction. The doublets were manually triggered at the peak of the maximal voluntary contraction. The activation levels were calculated as: $[1 - \text{superimposed twitch torque magnitude} / \text{control twitch torque magnitude}] * 100$ (Allen et al., 1998; Gandevia et al., 1998; Shield & Zhou, 2004). The average of four maximal voluntary repetitions was used to calculate the percent activation. Control twitches were elicited by stimulating the muscle in its resting state. Torque from the dynamometer was recorded during the superimposed maximal voluntary contractions and the control twitches.

The magnitude of electrical current applied to the muscle during twitch interpolation ranged from 100 to 400 milliamperes (mA) depending on the participant. Beginning with a very small current level of 50 mA, stimulus intensity was progressively increased in small increments. The appropriate level of stimulation was determined when no further increase in twitch torque response to stimulation was observed, or when the participant reached maximal intensity deemed tolerable. Once the appropriate current intensity was identified, the stimulus intensity was used for the superimposed twitch during maximal voluntary contractions, and the subsequent control twitch. This was completed on both the biceps and triceps brachii.

2.2.6 Electromyography

Maximal isometric muscle activation was assessed using EMG (Bagnoli-4, Delsys Inc., Boston, MA, USA) for elbow flexion and extension. The raw EMG signal was recorded for each of the four contractions on the isokinetic dynamometer for both the biceps brachii and triceps brachii during elbow flexion and extension. The biceps and triceps brachii electrodes were placed on the bulk of the muscle when the muscle was in a flexed position, and were located between the anode and cathode of the interpolated twitch electrodes according to the methods of Klein et al. (2001) (Figure 2.1). A reference electrode was placed on the knee cap to serve as a common ground for the EMG signal. Landmarking measurements were recorded after the first testing session to ensure correct placement at each testing time point. Prior to positioning the electrodes, the skin was prepared by shaving and cleaning the area with alcohol to reduce skin impedance values. Resting muscle signals were tested to limit signal noise, and where appropriate, electrodes were repositioned and the skin was re-shaven and cleaned to get a clear signal.

The EMG main amplifier unit included single differential electrodes with a bandwidth of 20 ± 5 Hz to 450 ± 50 Hz, a 12 dB/octave cutoff slope, and a maximum output voltage frequency of ± 5 V. The overall amplification or gain per channel was 1K for the biceps and triceps brachii muscles. The system noise was $<1.2 \mu\text{V}$ (rms). The electrodes were two silver bars (10 mm x 1 mm diameter) that were spaced 10mm apart, and had a Common Mode Rejection Ratio (CMRR) of 92 dB.

Additional muscle activation measurements were recorded in the training group only (Immob+train) once per week to monitor the amount of activation in the immobilized arm during strength training. The amplification or gain per channel was 1K for the training arm, and 10K

for the immobilized arm. During elbow flexion training, EMG electrodes were placed on the bulk of the biceps brachii muscles in both trained and untrained arms. The same technique was used for elbow extension with electrodes placed on trained and untrained triceps brachii muscles during training sessions. Muscle activation was recorded during the first and last set of the training session.

Raw EMG signals (in Volts) were converted to Mean Absolute Value (MAV) using Matlab (Version 7.3.0). MAV was used to get an estimate of the amplitude of the signal. It is measured as a function of time and was calculated using a defined window. A 0.5 second epoch immediately prior to the interpolated twitch was used to calculate the MAV. During the testing sessions, the average MAV from the four repetitions was used for comparison. During the weekly EMG measurements, the average MAV of the 8 repetitions was used. Post intervention MAV scores were normalized to the pre-scores to account for baseline differences between groups.

2.2.7 Data Acquisition

Custom software in Labview (Version 8.6) was used to obtain interpolated twitch, torque, and EMG (2 channels) data simultaneously. All channels were acquired at a sampling rate of 1000 Hz. An analog-to-digital (A to D) converter (NI PCI-6034E, National Instruments Corp, Austin, Texas) was used to convert the analog signals from each device to digital signals displayed in Labview.

2.2.8 Immobilization

Four weeks of unloading was achieved using a sling and swathe on the non-dominant arm (left arm in all participants). Previous slinging protocols by Parcell et al. (2000) and Miles et al. (2005) have effectively decreased muscle cross-sectional area and strength after 4 and 3 weeks, respectively. The sling suspended the elbow in a flexed position (elbow at approximately 90°) and the swathe held the arm against the torso. The sling was fitted for all participants to ensure the arm was at a 90° angle. The sling unloads the elbow flexor and extensor muscles and the swathe alleviates the shoulder muscles from supporting the arm and limits shoulder movement. The sling and swathe was worn during the waking hours to immobilize the arm. Participants removed the sling and swathe for sleeping and bathing and were required to record the number of hours the sling was worn, with a minimum of 12-14 hours per day. If participants removed the sling for any other cause, the reason for removal, duration of removal, day and time of removal was recorded. Participants were prohibited to use the immobilized arm from any type of work (i.e. lifting, pushing or pulling) and any type of stability/holding.

2.2.9 Data Analysis

Percent change was used to analyze strength and muscle thickness data to control for variability between participants. Percent change was calculated by subtracting the post-training score from the pre-training score, dividing by the pre-training score, and multiplying by 100. Strength was analyzed using a one-way independent measures ANOVA (group). Separate analyses were conducted for the right and left arm for each task (elbow flexion and extension). Separate analyses were conducted because the combined effect of the arms (main effect of “arm”)

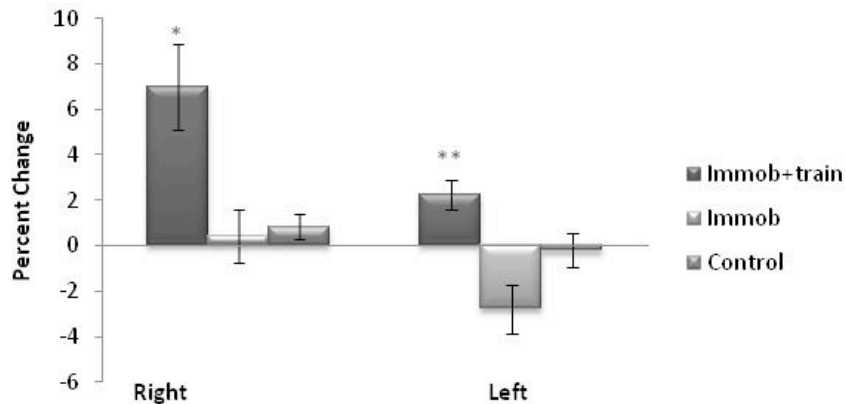
was not of interest to the researchers. Muscle thickness was analyzed using a one-way independent measures ANOVA (group). Separate analyses were conducted for the right and left arm for each muscle (biceps and triceps brachii). The interpolated twitch percent activation levels were analyzed separately using a between-within group (Immob+train, Immob, Control) \times time (pre, post) factorial ANOVA and using separate analyses for the right and left arm for each muscle (biceps and triceps brachii). For agonist EMG, MAV was normalized to the pre-scores due to baseline differences found between groups. The normalized agonist MAV scores were analyzed using a one-way ANOVA (group) with separate analyses for the right and left arm for each task (elbow flexion and extension). For antagonist EMG, a between-within group (Immob+train, Immob, Control) \times time (pre, post) factorial ANOVA with separate analyses for the right and left arm for each task (elbow flexion and extension) was used. If significant main effects or interactions were detected, simple main effects analysis continued using one-way ANOVA and Tukey's post hoc tests, or multiple comparisons with adjustment where appropriate. Significance was accepted at $P < 0.05$. All analyses were performed using SPSS version 17.0.

2.3 Results

2.3.1 Muscle Thickness

There were no significant differences at baseline for absolute muscle thickness values between the groups for either right or left arm. Univariate ANOVA for percent change in muscle thickness showed a significant main effect of group for the right biceps ($F(2,22) = 8.063, P = 0.002$) and triceps brachii ($F(2,22) = 7.846, P = 0.003$) and the left biceps ($F(2,22) = 8.884, P = 0.001$) and triceps brachii ($F(2,22) = 4.676, P = 0.02$). Post hoc analyses of

A. Biceps Brachii Muscle Thickness



B. Triceps Brachii Muscle Thickness

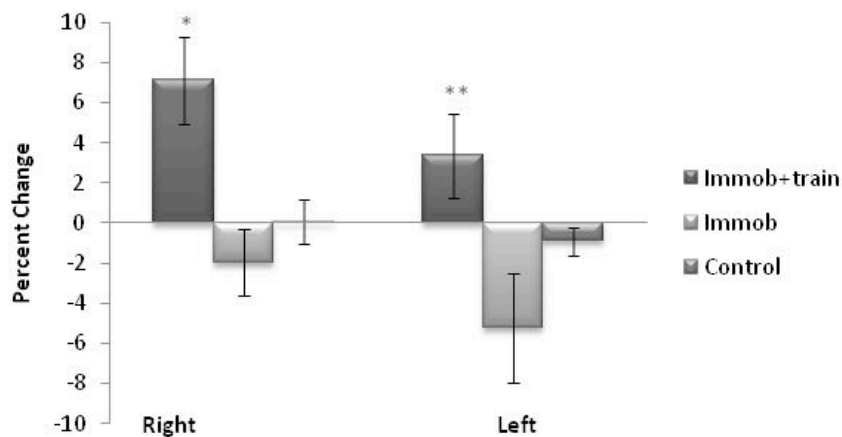


Figure 2.2 Biceps brachii and triceps brachii muscle thickness. Immobilization+train (Immob+Train) group received non-dominant, left limb immobilization (sling and swathe) and concurrently strength trained the free (right) arm. The Immobilization group (Immob) received non-dominant, left limb immobilization (sling and swathe) and did not strength train. Control group received no intervention. A: Biceps brachii muscle thickness percent change values \pm SE (standard error). Note that the right (free) arm of Immob+train was strength trained, and the left arm of the Immob+train and Immob groups wore the sling and swathe. B: Triceps brachii muscle thickness percent change values \pm SE. * Significantly different than Immob and Control ($P < 0.05$). ** Significantly different than Immob ($P < 0.05$).

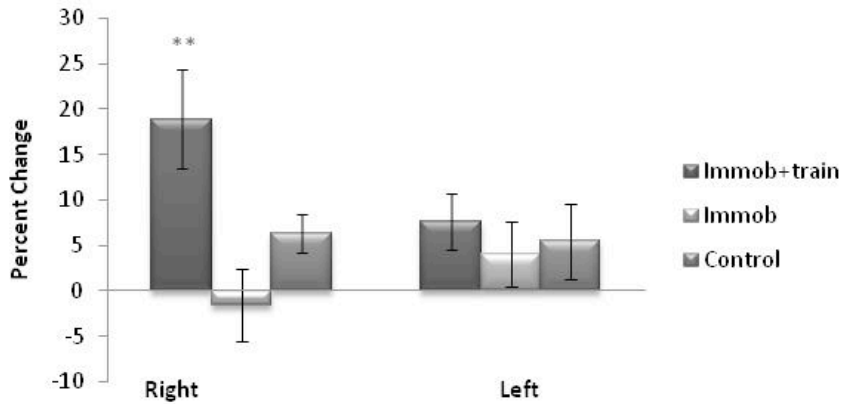
the right biceps brachii revealed Immob+train [7.0% (SE 1.9)] was significantly different than Immob [0.4% (SE 1.2)] and Control [0.8% (SE 0.5)] ($P < 0.05$). In the left biceps brachii, Immob+train [2.2% (SE 0.7)] was significantly different than Immob [-2.8% (SE 1.1)] ($P < 0.05$). For right triceps brachii muscle thickness, Immob+train [7.1% (SE 2.2)] was significantly different than Immob [-1.9% (SE 1.7)] and Control [0.0% (SE 1.1)]; and in the left triceps brachii, Immob+train [3.4% (SE 2.1)] was significantly different than Immob [-5.2% (SE 2.7)] ($P < 0.05$). Percent change muscle thickness data are presented in Figure 2.2.

2.3.2 Strength

Participants in the Immob+train group performed an average of 11.9 (SD 2.3) training sessions during the 4-week immobilization period (range of 9 to 14 training sessions completed). There were no significant differences at baseline for absolute strength values between the groups for either right or left arm. Univariate ANOVA for percent change in strength showed a significant main effect of group in right elbow flexion $F(2,22) = 6.478$, $P = 0.006$, and in right $F(2,22) = 5.975$, $P = 0.008$ and left elbow extension $F(2,22) = 8.070$, $P = 0.002$. Post hoc analysis for right elbow flexion showed Immob+train [18.9% (SE 5.5)] was significantly different than Immob [-1.6% (SE 4.0)] ($P < 0.05$). For right elbow extension strength, Immob+train [68.1% (SE 25.9)] was significantly different than Immob [1.3% (SE 7.7)] and Control [4.7% (SE 4.7)] ($P < 0.05$). In left elbow extension, Immob+train [32.2% (SE 9.0)] was significantly different than Immob [-6.1% (SE 7.8)] and Control [-0.2% (SE 4.5)] ($P < 0.05$). Note that the ANOVA for left elbow flexion was not significant. Percent change strength data are presented in Figure 2.3.

A.

Elbow Flexion Strength



B.

Elbow Extension Strength

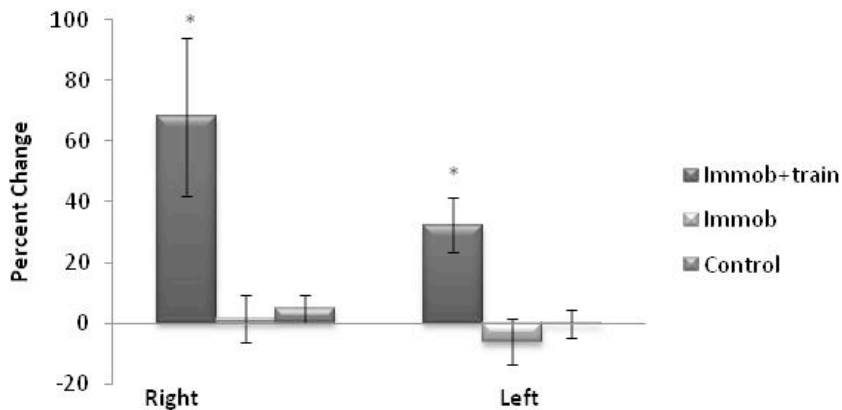


Figure 2.3 Elbow flexion and elbow extension strength. A: Biceps brachii strength percent change values \pm SE (standard error). Note that the right (free) arm of Immobilization+train (Immob+train) was strength trained, and the left arm of the Immob+train and Immob groups wore the sling and swathe. B: Triceps brachii strength percent change values \pm SE. * Significantly different than Immob and Control ($P < 0.05$). ** Significantly different than Immob ($P < 0.05$).

Table 2.2 Percent activation via interpolated twitch. Values are means (\pm SD).

	Elbow Flexion (biceps brachii)				Elbow Extension (triceps brachii)			
	R Pre	R Post *	L Pre	L Post	R Pre	R Post	L Pre	L Post
Immob+train	88.1 (8.4)	94.5 (5.4)	90.3 (4.8)	91.2 (10.6)	90.1 (5.0)	93.5 (6.9)	91.6 (5.3)	90.3 (10.1)
Immob	92.2 (4.7)	94.3 (4.5)	91.5 (4.6)	89.7 (9.1)	93.1 (5.2)	92.7 (4.4)	87.1 (7.0)	90.4 (8.3)
Control	91.7 (6.4)	94.1 (5.6)	93.4 (4.1)	90.6 (7.5)	94.0 (4.6)	90.4 (9.1)	87.5 (10.2)	88.1 (10.3)

R, Right; L, Left. * Significant time main effect for right elbow flexion in all groups pooled ($P < 0.05$).

Table 2.3 Agonist activation via EMG. Values are means (\pm SD) normalized to pre-scores.

	Elbow Flexion (biceps brachii)		Elbow Extension (triceps brachii)	
	R	L	R	L
Immob+train	1.053 (0.321)	0.912 (0.276)	1.392 (0.625)*	1.148 (0.501)
Immob	0.988 (0.290)	0.994 (0.329)	1.033 (0.248)	0.934 (0.250)
Control	1.133 (0.308)	1.025 (0.332)	0.872 (0.211)	0.942 (0.283)

R, right; L, left. * Significant difference between Immob+train and Control ($P < 0.05$).

Table 2.4 Antagonist activation via EMG (mV). Values are raw means (\pm SD).

Elbow Flexion				
	R Pre	R Post	L Pre	L Post
Immob+train	0.043 (0.045)	0.030 (0.010)	0.040 (0.034)	0.025 (0.008)
Immob	0.031 (0.017)	0.027 (0.017)	0.024 (0.010)	0.025 (0.012)
Control	0.024 (0.007)	0.029 (0.010)	0.022 (0.006)	0.027 (0.012)
Elbow Extension				
	R Pre	R Post	L Pre	L Post
Immob+train	0.029 (0.010)	0.034 (0.008)	0.028 (0.009)	0.030 (0.006)
Immob	0.031 (0.005)	0.035 (0.017)	0.034 (0.009)	0.032 (0.017)
Control	0.027 (0.005)	0.029 (0.008)	0.025 (0.005)	0.024 (0.003)

R, right; L, left; mV, millivolts. No significant differences found. Note: The antagonist muscle in elbow flexion is the triceps brachii. The antagonist muscle in elbow extension is the biceps brachii.

2.3.3 Percent Activation via Interpolated Twitch

Univariate ANOVA revealed a significant time main effect for elbow flexion in the right biceps brachii for all groups pooled $F(1,22) = 6.696$, $P = 0.017$). No other significant differences for percent activation were detected. Percent activation data are presented in Table 2.2.

2.3.4 Electromyography (EMG)

The ANOVA for agonist MAV activation (normalized to pre scores) revealed a significant main effect of group for right elbow extension $F(2,22) = 3.702$, $P = 0.041$). Post hoc analysis showed there was a significant difference between Immob+train [1.392 (SD 0.625)] and Control [0.872 (SD 0.211)] ($P < 0.05$). There were no other significant differences for agonist MAV activation in elbow flexion or extension. Agonist MAV activation is presented in Table 2.3. For antagonist MAV activation, there were no significant differences found ($P > 0.05$). The magnitude of antagonist muscle activation was minimal for all participants. Antagonist activation is presented in Table 2.4. For the weekly EMG (conducted in Immob+train only), the immobilized biceps brachii was activated at a level of 3.1% (SD 0.9) of the training biceps brachii during strength training, and the immobilized triceps brachii was activated 6.1% (SD 2.0) of the training triceps brachii during strength training (pooled across the 4 week intervention).

2.4 Discussion

The main finding of the present study was that strength training the non-immobilized limb provided a beneficial effect for muscle thickness and strength in the immobilized limb after 4 weeks of wearing a sling and swathe. The cross-education effect was much more pronounced

with elbow extension compared to elbow flexion training. The present study also found that the immobilization had no effect on maximal voluntary activation or amplitude of muscle activation (MAV), and that there were minimal levels of activation in the immobilized limb during unilateral strength training of the right limb.

An interesting finding in the present study is that there was a significant difference between Immob+train and Immob for muscle thickness in the immobilized biceps and triceps brachii. The immobilized biceps and triceps brachii in Immob+train showed positive changes in muscle thickness (2.2% in biceps brachii and 3.4% in triceps brachii, not significantly different than control), whereas Immob showed negative changes in muscle thickness (-2.8% in biceps brachii and -5.2% in triceps brachii, not significantly different than control) (Figure 2.2). This suggests that muscle size loss may have been attenuated for the Immob+train group in both muscles. However, it is difficult to draw conclusions from these findings since the changes were not significantly different than the control group. A previous study in our lab showed a maintenance effect in the immobilized limb using a forearm casting protocol (Farthing et al., 2009). The mechanism for the prevention of muscle size loss is not known, however Farthing et al. (2009) suggest that unilateral strength training of the non-immobilized limb may have provided a large enough stimulus to the motor system to prevent muscle atrophy in the immobilized limb. Muscle size loss may have also been prevented from motor unit activation in the immobilized arm during unilateral strength training of the free arm (Farthing et al., 2009). The sling and swathe protocol allowed us to better test this theory in comparison to casting protocols which limit convenient access of the target muscles. The sling and swathe was removable, therefore during the strength training sessions motor unit activation of the immobilized arm was monitored via EMG to determine the level of activation. Results showed

that the amount of activation in the immobilized arm during strength training was minimal. The immobilized arm was activated 4.6% (average of biceps and triceps brachii) of the training arm during strength training contractions. Other cross-education studies have shown small amounts of activation in the non-training limb during strength training (Hortobágyi et al., 1997; Farthing et al., 2005); however, the amount of activation is so small that it is unlikely to provide enough of a stimulus to produce a maintenance in muscle size (Farthing et al., 2009).

A fascinating result of the present study is that strength training the non-immobilized arm produced a significant and large increase in strength in the immobilized arm for elbow extension (32.2%) after 4 weeks of wearing the sling and swathe (Figure 2.3). This increase in strength is consistent with the magnitude of cross-education that would be expected without an immobilization intervention. Conversely, the Immob group (conducted no strength training) declined in strength by 6.1% in the immobilized arm (Figure 2.3), although not significantly different than control. To our knowledge, this prominent increase in strength after a period of immobilization has not been previously demonstrated. Farthing et al. (2009) found that strength was maintained, but not enhanced in the immobilized arm after applying cross-education using a 3-week casting protocol. This large increase in strength in the immobilized arm may be due to alterations in muscle recruitment that may not be associated with the target muscles. Agonist and antagonist activation in Immob+train was not significantly different than Immob or Control (Tables 2.3 and 2.4), and therefore cannot account for the large increase in strength. Activation of the homologous agonist muscle in the immobilized limb during strength training sessions was monitored; however minimal activation was detected. It is possible that activation of other muscles not monitored in the immobilized limb contributed to the large increase in strength. Immob+train may not have been able to better activate the target muscles (no change in percent

activation or EMG), however they may have been able to better coordinate or stabilize the joint. This may be due to both flexion and extension exercises being a part of the strength training program. No other cross-education study has used two opposing exercises to strength train; therefore the effect of the two exercises across the joint could have contributed to the large increase in strength for elbow extension.

Although the present study did not investigate neural mechanisms in the brain, it has been suggested that cross-education may be due to changes in motor learning. These changes may include plasticity in the brain, particularly in the primary motor cortex, premotor cortex, or supplementary motor area (Farthing, 2009). Unilateral strength training produces changes in brain activation in both hemispheres with the untrained limb showing increased activation in the contralateral sensorimotor cortex and ipsilateral temporal lobe, suggesting that changes in the brain are being shared between hemispheres (Farthing et al., 2007). In the present study, evidence of motor learning may be indicated by the fact that the magnitude of cross-education was so high despite the untrained limb being immobilized for 4 weeks and by the finding that there was no change in muscle activation. Spinal mechanisms may also play a role in cross-education; however it has been shown that after an increase in strength in both trained and untrained limbs, increased spinal excitability was found only in the trained limb (Lagerquist et al., 2006). Lagerquist et al. (2006) suggested that supraspinal mechanisms contributed to the increase in strength in the untrained limb. More research into the mechanisms of cross-education needs to be conducted to better understand these effects.

A puzzling finding was that a decrease in elbow flexion strength was not found in the immobilized arm of the Immob group (Figure 2.3). Previous research has shown decreases in strength following immobilization (Parcell et al., 2000; Miles et al., 2005). This questions

whether or not the immobilization protocol had an effect; however we did find a decrease in elbow extension strength (-6.1%) (significantly different than Immob+train but not control) and a decrease in muscle size for the biceps (-2.8%) and triceps brachii (-5.2%) (significantly different than Immob+train but not control). Reasons for this finding may be that the 4-week intervention period was not long enough to induce decreases in strength, or that the participants were not as compliant as they reported in the daily immobilization logs.

It was hypothesized that Immob+train would maintain elbow flexion strength in the immobilized arm, therefore demonstrating the cross-education effect to an immobilized limb. As stated above, all three groups increased left arm strength slightly, but no significant differences between groups were found (Figure 2.3). The non-significant finding of cross-education for elbow flexion was possibly due to the smaller gain in magnitude in the training arm for elbow flexion. Immob+train increased strength in the training arm by 18.9% compared to a 68.1% increase for elbow extension. On average, cross-education is 52% of the strength gained in the trained muscle (Carroll et al., 2006). The strength gain from the trained to untrained muscle was approximately 47% for elbow extension and 41% for elbow flexion. The increase in untrained arm strength relative to the trained muscle in both elbow extension and elbow flexion was similar (47% and 41%, respectively). The trained arm in Immob+Train had a small increase in elbow flexion strength and the Immob and Control groups had a trend to increase elbow flexion strength, which likely accounted for the non-significant effect.

The lack of cross-education observed for elbow flexion may have also been due to the task itself. Cross-education has been shown to have a greater effect in more unfamiliar tasks (Farthing et al., 2005; Farthing, 2009). The elbow flexion task was quite simplistic and easy to execute with consistency. It required the participants to pull towards themselves with the hand

supinated. The elbow extension task was more unfamiliar whereby it required the participants to push away from themselves with the hand internally rotated from the supinated position 90°. More complex strength tasks require coordination and recruitment of multiple muscle groups, therefore greater motor learning adaptations in response to strength training are evident (Farthing, 2009). However, in the present study the control group showed no significant increase in strength for either strength task, suggesting that the strength training intervention was responsible for any motor learning adaptation that contributed to the cross-education effect.

The immobilization unloading protocol using the sling and swathe had a greater effect on muscle thickness than on strength (Figure 2.2 and Figure 2.3). It has previously been shown that the position the muscle is placed in may influence changes in muscle morphology (Summers & Hines, 1951; Goldspink, 1977; Gossman et al., 1982; Booth et al., 1996). When muscles are fixed in a shortened or neutral position they will likely atrophy; however when muscles are fixed at a lengthened position beyond neutral, muscle atrophy may be attenuated or prevented, and in some cases muscle hypertrophy can occur (Summers & Hines, 1951; Goldspink, 1977; Gossman et al., 1982). The present study found that the biceps brachii in Immob decreased muscle size by 2.8% and the triceps brachii decreased by 5.2% (not significantly different than control) (Figure 2.2). The reason for the larger decline in muscle thickness in the triceps brachii than the biceps brachii is not known. The placement of the elbow joint at 90° elbow flexion may not have been lengthened enough to maintain muscle size. A further decrease in the elbow flexion angle may have led to different results.

The changes in the muscle for the Immob group are consistent with changes found in other research studies that have immobilized healthy limbs. Significant decreases in elbow flexor volume (7.7%) and elbow flexion strength have been found (Miles et al., 2005), as well as

significant decreases in triceps brachii cross-sectional area (4%) and elbow extension strength (12%) (Parcell et al., 2000) after arm sling unloading. Both of these studies, along with the present study allowed participants to remove the sling during sleeping and bathing. A 4-week casting study on the elbow joint found that the elbow flexors significantly decreased cross-sectional area (11.2%), but showed a non-significant decline in force, whereas the elbow extensors had non-significant declines in cross-sectional area and maximal voluntary force (Yue et al., 1997). More research is needed to understand the effects of immobilization protocols on different muscle groups in the upper limb.

The present study also examined changes in maximal voluntary muscle activation following immobilization. Results showed a significant time main effect for right elbow flexion in all groups pooled, however there were no other significant changes detected (Table 2.2). These results indicate that the immobilization protocol had no effect on the ability of the muscles to maximally activate. Gondin et al. (2004) found maximal voluntary activation decreased by 6% after ankle immobilization. Similarly, other studies have found that immobilization decreased the ability to maximally activate the muscles (Behm & St.Pierre, 1997; Thom et al., 2001; Deschenes et al., 2002); however, these studies were conducted on injured participants where the effects of the injury undoubtedly hindered the ability to maximally contract. A study using cross-education alone (i.e. training without immobilization) found no change in maximal voluntary activation in the non-training limb (Yu et al., 2008). From this observation, if a decrease in activation was present (i.e. after an injury) it may be speculated that there would not be a maintenance effect for muscle activation in the immobilized limb after cross-education training. However, the cross-education effect may still be beneficial for an injured limb

compared to when no contralateral training is completed. This is an important question for future work.

A limitation to the method of using interpolated twitch to predict percent activation is that when using inexperienced participants, the expectation of a stimulus during a maximal contraction may significantly decline both strength and percent activation (Button & Behm, 2008). This may have influenced the present study where the force and percent activation levels recorded may actually be lower than if there was no anticipated stimulus during the maximal contraction. However, since all participants in the present study were inexperienced, it would be expected that all groups would show a similar response to the stimulus.

The present study also investigated changes in EMG activity, and found for normalized agonist MAV activity, there was a significant difference for right elbow extension between the Immob+train and Control group (Table 2.3). This difference reflects the increase in muscle activation after strength training the right arm of Immob+train, which is consistent with previous strength training studies (Mortani & deVries, 1979; Hortobágyi et al., 1997; Shima et al., 2002). There were no other significant differences for activation amplitude in either agonist or antagonist muscles. Wearing the sling and swathe for 4 weeks appeared to have no effect on the electrical activity of the immobilized muscles. Farthing et al. (2009) also found no change in MAV activity after 3 weeks of forearm casting. Yue et al. (1997) looked at changes in EMG in the biceps and triceps brachii after elbow immobilization and found a decrease in biceps brachii activation after 4 weeks; however the effects on the triceps brachii were not reported. Other studies have found decreases in the amplitude of the EMG signal after immobilization (Deschenes et al., 2002; Parcell et al., 2000) making results inconsistent as to whether short-term

immobilization leads to reductions in muscle activation. The difference in studies may be due to different types and durations of immobilization as well as the muscles being immobilized.

A limitation to the present study is that we could not be absolutely sure of how compliant the participants were in wearing the sling and swathe. Participants were instructed to wear the sling and swathe for a minimum of 12-14 hours per day and record in daily journals anytime it was removed. From the daily journals, the sling and swathes were removed for reasons such as showering, sleeping, and driving, and were worn for an average of 13.0 hours per day (Immob+train and Immob averaged) (Table 2.1). An improved model to ensure compliance may be to use an elbow cast; however we were interested in the effects of the sling and swathe due to its wide use in clinical practice after upper limb injuries (i.e. shoulder surgery). We were also interested in conveniently monitoring muscle activation of the immobilized arm during strength training of the free arm, which required access to the target muscles.

The purpose of the present study was to apply cross-education during 4-weeks of unilateral limb immobilization using a shoulder sling and swathe to investigate the effects on muscle strength, muscle size, and muscle activation. The results suggest that strength training the non-immobilized limb provided a benefit to the immobilized limb in healthy participants. These findings have the potential for application to real injuries where strength training of the healthy limb may provide a beneficial effect to the injured limb. The extent of the benefits in an injured population are not known, therefore these results should be taken with caution when considering real injuries. This study was unique in that it was the first cross-education study to investigate the effects on the contralateral limb with two opposing strength training exercises. Another novel aspect of this study was that we were able to monitor muscle activation in the immobilized limb during unilateral strength training of the free limb. The amount of activation

in the immobilized limb was minimal, therefore not likely to be a mechanism of the cross-education effect in this context. In conclusion, cross-education seems to be beneficial for preventing the harmful effects of unilateral limb immobilization in healthy participants; however more research is needed to further investigate the effects in a clinical population.

2.5 Relation of Experiment 1 to Thesis

The first objective of the thesis was to determine if cross-education could improve strength and functional performance of an immobilized limb using a shoulder sling model in both healthy and injured participants. Study one was one of three studies necessary to meet the first objective. The purpose of the study was to determine if cross-education could benefit strength, muscle size, and muscle activation in an immobilized healthy limb using a shoulder sling and swathe model in healthy participants. This study was needed to extend the literature on cross-education immobilization models in healthy participants. Previous literature had investigated the effect in forearm casting models (Farthing et al., 2009; 2011); however, no studies had determined if the effect could be replicated in other model settings.

Chapter 3: Experiment 2

Experiment 2 has been recently accepted for publication in a peer-reviewed sports medicine journal (Title: At-home resistance tubing strength training increases shoulder strength in the trained and untrained limb). It is presented in the accepted form with the exception of some minor changes necessary for the conversion to graduate thesis format.

3.1 Introduction

The contralateral effect of unilateral strength training (i.e. cross-education of strength) is well documented, with growing interest in the potential for cross-education to be used in rehabilitation settings (Dale, 2005; Carroll et al., 2006; Farthing, 2009; Farthing et al., 2009; Magnus et al., 2010). However, the vast majority of studies in the literature have focused on cross-education effects after conventional or lab-based forms of isometric or dynamic strength training (Kannus et al., 1992; Hortobágyi et al., 1997; Farthing & Chilibeck, 2003; Farthing et al., 2005; Munn et al., 2005; Dragert & Zehr, 2011; Hortobágyi et al., 2011; Latella et al., 2012). The average increase in strength of the untrained limb is about half of the increase in strength of the trained limb (Carroll et al., 2006). Much less attention has been paid to cross-education effects after implementing more therapeutically relevant and feasible “at-home” resistance training programs such as those utilizing resistance tubing or stretch bands.

Although cross-education has potential in shoulder rehabilitation (i.e. recovery from surgery), to our knowledge there is currently no research to determine if a therapeutically relevant unilateral strength training program targeting the shoulder produces increases in strength in the untrained limb. It seems reasonable to predict similar cross-education effects after unilateral shoulder training as compared to other upper body tasks such as handgrip (Farthing et

al., 2005) and elbow flexion (Magnus et al., 2010); however it is important to quantify the magnitude of the effect using a training protocol that is feasible for shoulder injury patients, and easy to incorporate into rehabilitation programs already in place (i.e. tubing exercise).

Traditionally, cross-education studies have only used one exercise to show increases in strength in the untrained limb (Carroll et al., 2006; Farthing, 2009). Cross-education effects may be shown if only one shoulder exercise is used; however, if applying to a shoulder rehabilitation setting the goal would be to strengthen the entire shoulder joint. Therefore, multiple exercises targeting the shoulder may be more clinically relevant, and more feasible to see cross-education compared to only using a single exercise.

Shoulder injuries are one of the most common types of injury (Holtby & Razmjou, 2010) resulting in impairment, shoulder dysfunction (Millett et al., 2006), and typically long rehabilitation periods (Conti et al., 2009). Six to eight months after rotator cuff surgery the decline in strength ranges from 15-36% (Binet et al., 2003) and even after 5 years of rehabilitation, a decline in strength still remains (Rokito, 1999). Typical rehabilitation after a shoulder injury consists of physical therapy incorporating range of motion exercises and strengthening of the injured limb using a home-based exercise program. Home-based strength training programs significantly increase strength in the upper and lower body (Mikesky et al., 1994; Andersen et al., 2011); however, the equipment is limited due to the cost, space and the convenience of using exercise equipment and resistance tubing is commonly used. Resistance tubing (i.e. elastic bands) is frequently used in rehabilitation settings, and is feasible for home-based exercise programs. Strength training with resistance tubing can improve strength (Mikesky et al., 1994; Andersen et al., 2011) and show similar muscle activation patterns compared to dumbbells (Andersen et al., 2010). Behm (1991) showed that there was no

significant difference in strength gain when comparing resistance tubing and two different types of machine weights after a 10-week shoulder strength training program. There is currently no data on cross-education effects after unilateral training using resistance tubing exercise.

Both home-based strength training and resistance tubing are effective for increasing strength; therefore, a combination of the two may be feasible to produce cross-education effects in the shoulders, and may provide a practical strategy to improve shoulder rehabilitation. The purpose of the present study was to determine if an at-home resistance tubing strength training program on one shoulder would produce increases in strength in both the trained and untrained shoulders. Our hypothesis was that an at-home resistance tubing strength training program on one shoulder would show increases in strength on both shoulders via cross-education.

3.2 Methods

3.2.1 Participants

A power calculation was completed using G Power 3.1 (Faul et al., 2009) to calculate the sample size. A review of previous upper body cross-education studies (Farthing, 2009) was used to determine the average increase in strength of the untrained limb was 22%. However, a conservative estimate of a 15% increase in strength of the untrained limb was used to estimate sample size since this was an unsupervised at-home strength training program. The average effect size was determined to be 0.45 from a separate sample of 10 participants when using strength data from 3 shoulder strength measures (external rotation, internal rotation, and scaption). Using α of 0.05 at 95% power, it was determined that the total sample size needed was 20 (i.e. 10 participants per group). A total of 27 participants were recruited for the study to account for dropouts. Prior to commencement of the study, all participants signed informed

written consent approved by the Biomedical Ethics Review Board at the University of Saskatchewan (see Appendix B for Certificate of Approval). Participants were excluded from the study if they had any current shoulder or upper body injuries interfering with daily life. All participants completed the Waterloo Handedness Questionnaire (WHQ) to determine handedness. The WHQ is scored from -20 to +20, where negative scores indicate left-handedness, and positive scores indicate right-handedness. There were 22 right-handed participants, and 1 left-handed participant. The means of the absolute handedness scores are shown in Table 3.1. Participants had a mean age of 50.0 ± 9.0 years, height of 168.9 ± 10.6 cm, and weight of 83.8 ± 19.5 kg, with no significant difference between groups. Resistance training experience for the past year was self-reported (in months) by the participants where 1 month of resistance training consisted of strength training a minimum of 3 times/week for 4 weeks. There was a significant difference between the groups where Control (no intervention) (8.5 ± 4.1 months) had more experience than Train (completed the strength training intervention) (1.9 ± 3.6 months). All participants were asked to maintain their normal daily lifestyle throughout the study. Participant descriptives are shown in Table 3.1.

3.2.2 Design

The design of this study was a between-within (mixed) design. Dependent measures were strength (external rotation, internal rotation, scaption, and handgrip) and muscle thickness (supraspinatus, and anterior deltoid). The primary researcher randomized participants after the initial testing was completed using a random computer number generator. Participants were split into one of two groups: Train or Control. Train had 13 participants (6 men, 7 women) and Control had 10 participants (5 men, 5 women). Train completed a shoulder strength

Table 3.1 Participant descriptive statistics for each experimental group. Values are means (\pm SD).

	Train (n=13)	Control (n=10)
Height, cm	167.5 (8.5)	170.8 (13.1)
Weight, kg	79.0 (13.0)	90.1 (25.1)
Age, yr	47.7 (6.0)	53.1 (11.4)
Training Experience, months	1.9 (3.6)	8.5 (4.1) *
Handedness Score, WHQ	18.0 (2.1)	17.4 (2.7)

WHQ reported as absolute scores. * Training Experience (months) significantly different between Train and Control ($P<0.05$).

training program on one arm only, whereas Control had no intervention. In Train, participants were randomly selected to strengthen either their dominant or non-dominant arm. Although there is evidence of enhanced cross-education from dominant to non-dominant limb (Farthing et al., 2005; Farthing, 2009), we randomly selected the training limb in this experiment to be more applicable to injury rehabilitation settings where cross-education might be applied to either limb. Six participants strength trained their dominant arm, and 7 participants strength trained their non-dominant arm. For the purpose of presenting the data, the terms training arm and non-training arm were used instead of left arm and right arm. For Control, training arm and non-training arm were randomly selected since this group did not have a training arm (5 participants were randomly selected to have their right arm as the training arm, and 5 participants were randomly selected to have their left arm as the training arm). All participants completed 2 testing sessions (pre and post) 4 weeks apart, and were familiarized to the strength testing procedures prior to completing the testing to limit any learning effects.

3.2.3 Strength Testing and Training

Maximal isometric shoulder strength (external rotation, internal rotation, and scaption) was assessed on both arms using a hand-held dynamometer (Lafayette Manual Muscle Test System, Lafayette Instrument, Lafayette IN). Hand-held dynamometry was chosen, as it is portable, clinically relevant, and has been shown to be valid and reliable (Bohannon, 1986; Sullivan et al., 1988; Magnusson et al., 1990). The coefficient of variation for the hand-held dynamometer was found to be 4.5% for external rotation, 4.3% for internal rotation, and 4.4% for scaption using a separate sample of 10 participants.

The three shoulder motions of external rotation, internal rotation, and scaption (abduction of the extended arm in the scapular plane, 30 degrees anterior from the coronal plane) were tested in a seated position with the feet flat on the floor (See Appendix C for picture of testing positions). The dynamometer was placed just above the wrist (proximal to the ulnar styloid process) (Reinold et al., 2008). For external and internal rotation, the elbow was bent at 90 degrees with the shoulder at 0 degrees of abduction. The elbow rested alongside the participant's body with the forearm anterior to the body and the hand in neutral position (palm facing medially). Scaption was tested with 0 degrees of flexion at the elbow, and with the arm abducted 20 degrees from the body, and 30 degrees anterior from coronal plane of the body. The wrist was in neutral position with the palm facing down. The motions of external rotation, internal rotation and scaption were chosen as outcome measures of strength because they are clinically relevant to shoulder injuries such as rotator cuff tears. Two additional strength training exercises (retraction and shoulder flexion) were included in the training program but not in the strength testing for feasibility; additional strength testing measures would increase the total time commitment of participants, as well as increase fatigue of the shoulder muscles during the testing. The contractions were 3-seconds long, with the best of 3 repetitions recorded as the peak strength (kg). Participants were instructed to progressively increase force within each individual contraction so they reached maximal force at the end of the 3-seconds. In the event that the body position of the participant moved, additional repetitions were performed. The order of testing was the same for all participants (external rotation, followed by internal rotation, scaption, and then handgrip). Left and right arm were alternated during the testing, followed by a minute rest between each testing round.

Handgrip strength (kg) was assessed on both hands using a handgrip dynamometer (JAMAR dynamometer, JA Preston Corp., Jackson, MI) in the seated position with the elbow bent at 90 degrees. This position was chosen because it is the testing position used in most clinical settings and is recommended by the American Society of Hand Therapists (Innes, 1999). Handgrip strength was assessed to provide a global estimate of upper body strength for both groups. Handgrip contractions were 3-seconds long with the best of 3 repetitions used as the peak. Verbal encouragement was given for all strength testing measurements.

Strength training for Train was conducted at home for all participants using resistance tubing on one arm only (either dominant or non-dominant arm). The training was 4-weeks long and was conducted 3 times/week. Participants were instructed to leave a day rest between training sessions. All training participants received a phone call 1-week after beginning of training to ensure they were compliant with the exercises.

The training program consisted of both dynamic and isometric sets for the following exercises: external rotation, internal rotation, scaption, flexion, and retraction. These exercises were chosen to adequately strengthen all muscles surrounding the shoulder. Dynamic exercises were used to replicate resistance tubing strength training commonly used in rehabilitation settings, and isometric exercises were used for specificity to the isometric exercise testing. The strength training program was progressive, beginning with 1 set of dynamic and 1 set of isometric exercises for each movement. After one week, training progressed to 2 sets of dynamic and 2 sets of isometric exercises for each movement. In the last week of the program, the training load was reduced to 1 set dynamic and 1 set isometric for each exercise to serve as a taper. Participants were instructed to complete 10-15 repetitions to failure for each set and leave

a minute rest between sets. Non-compliance was defined as completing less than 8 out of 12 training sessions.

Four different strengths of resistance tubing with handles (Leonard Fitness Inc., China, Workoutz.com) were given to each training participant. The strengths were coded by different colors beginning with yellow for light exercise and beginners (1.8-2.3 kg resistance), red for medium to heavy exercise (4.1-4.5 kg resistance), blue for moderately trained individuals (5.5 kg resistance), and black for trained athletes (7.3 kg resistance). A Canadian Society for Exercise Physiology - Certified Exercise Physiologist (CEP) taught the exercises to participants in the training group at the initial testing session, and the program was conducted unsupervised at home. The repetition timing for dynamic exercises was 2-seconds in the concentric phase of the contraction, and 2-seconds in the eccentric phase of the contraction while using the appropriate exercise tube to maintain resistance throughout the contraction. Repetitions for static exercises were held for 3-seconds and were completed using the strongest tube (black) to hold the contraction in the desired position. The repetition timing of the contractions were not directly monitored (e.g. via metronome), as it was not feasible for participants to monitor repetition timing with the at-home training program. Training participants were instructed how to count the seconds for each contraction in order to execute the correct timing. The position for static exercises was the same position as the strength testing was completed for external rotation, internal rotation, and scaption. The hold position for flexion was 20 – 30 degrees away from the body and retraction was at the end range of motion. The training group was instructed to complete each dynamic and static set to failure, and was taught how to increase resistance either by using the same tube and modifying the length, or by changing tubes to the next highest resistance. There was no set anchor point marked on the tubing for participants to execute the

exercises from due to the changing resistance of each exercise as participants progressed throughout the program. Participants were also instructed to relax the non-training limb during the training to limit any mirror activity of the non-trained limb.

The Borg Scale of Rated Perceived Exertion (Borg CR10) (Borg, 1998) was used after each training session to gauge the difficulty of the exercises. The Borg CR10 scale has previously been shown to be useful in estimating intensity of exercises in individual rehabilitation protocols (Andersen et al., 2010). Participants were instructed to work in the 5-10 range (strong to very, very strong) of the scale to ensure the exercises remained challenging. A training log was used to record the repetitions for each set and the difficulty of each exercise.

3.2.4 Muscle Thickness

Muscle thickness of the supraspinatus and anterior deltoid was assessed pre and post intervention using a portable US scanner (LOGIQ e BTO8, GE Healthcare) equipped with a linear (38.4 mm) 12 Hz transducer (resolution 0.3mm). Muscle thickness was used as an indicator to assess any changes in the muscle as a result of the training program. Ultrasound has previously been used in other studies to monitor changes in the muscle after strength-training interventions (Farthing et al., 2005; Farthing et al., 2009; Magnus et al., 2010). The supraspinatus was chosen, as it is the rotator cuff muscle most commonly injured (Cofield et al., 2001), and is superficial to the skin surface; therefore, can easily be measured with ultrasound. The anterior deltoid was chosen, as it is a superficial shoulder muscle that is easy to access and view with ultrasound, and is a muscle that can easily be landmarked. The supraspinatus measurement was taken 4 cm medial to the most medial point of the acromioclavicular joint on the bulk of the muscle. The anterior deltoid landmark was located by placing the probe on the

bulk of the muscle on the anterior aspect of the shoulder. The location was approximately 7 cm down from the uppermost point of the shoulder in line with the midpoint of the anterior deltoid. Both muscles were measured with the arm in a relaxed position, resting on the participant's lap. Sagittal images were taken with the ultrasound probe placed perpendicular to the muscle (See Appendix D for picture of supraspinatus ultrasound image). Minimal pressure was applied to the probe to avoid deforming the underlying tissues.

Muscle thickness was assessed prior to any strength testing. Both shoulders were measured with a stringent landmarking method using an overhead transparency film to ensure identical location at the pre and post-test (Farthing & Chilibeck, 2003). The left arm was always measured first to ensure standardized timing of the procedure. At each location, four measurements were taken with the average of the closest two measurements used for comparison. Additional measurements were taken if any two of the four measurements were not within 1 mm to ensure precision. The coefficient of variation for ultrasound to assess muscle thickness was found to be 3.7% (average of supraspinatus and anterior deltoid) using a separate sample of 10 participants in our lab.

3.2.5 Data Analysis

All analyses were carried out using SPSS (version 20). Raw data for the three shoulder strength motions of external rotation, internal rotation, and scaption were analyzed together using a multivariate group (Train, Control) X time (pre, post) X arm (trained arm, untrained arm) analysis of variance appropriate for multiple dependent variables with repeated measures. Handgrip strength was analyzed separately as it was used to monitor global strength changes and was not part of the strength training program. Raw data for handgrip strength was analyzed

using a group (Train, Control) X time (pre, post) X arm (trained arm, untrained arm) repeated measures ANOVA. Percent change for all strength measures was calculated by subtracting the post score from the pre score, dividing by the pre score, and multiplying by 100. Percent change for the three shoulder measures was analyzed using a group (Train, Control) X arm (trained arm, untrained arm) multivariate analysis for repeated measures to simplify the results and allow comparison of the magnitude of the trained and untrained arms. Handgrip percent change was analyzed for consistency of the strength analysis using a group (Train, Control) X arm (trained arm, untrained arm) factorial ANOVA. For muscle thickness, the supraspinatus and anterior deltoid were analyzed together using group (Train, Control) X time (pre-post) X arm (trained arm, untrained arm) multivariate analysis of variance for repeated measures. If significant main effects or interactions were detected, simple main effects analysis continued followed by paired t-tests. Significance was accepted at $P < 0.05$ with Bonferroni adjustments made where appropriate (i.e. $0.05/4 = 0.0125$). Means and standard deviations of data are reported in text and tables. In figures, means and standard errors are reported to improve readability of the graphs.

3.3 Results

3.3.1 Strength

Twenty-three participants were included in the final data analysis. Two participants dropped out due to the time commitment of the study, and one participant did not finish the study due to an unrelated injury. In addition, one participant in Train was removed from the analysis due to non-compliance with the strength training program. All participants in Train completed 12 training sessions during the 4-week strength training program. Training participants reported a perceived exertion ranging from 4 to 10 for the shoulder exercises. The number of reported

repetitions ranged from 5 to 20 per set (target number of repetitions was 10-15 per set). There were no significant differences between groups at baseline for external rotation, internal rotation, scaption, or handgrip strength. There was a significant group X time multivariate interaction ($F(3,19)=4.269$, $P=0.018$, Partial $\eta^2=0.40$) for the 3 shoulder strength measures. Univariate ANOVA revealed significant group X time interactions for external rotation ($F(1,21)=9.329$, $P=0.006$, Partial $\eta^2=0.31$) and internal rotation ($F(1, 21)=8.479$, $P=0.008$, Partial $\eta^2=0.29$) and significant time main effects for external ($F(1,21)=6.880$, $P=0.016$ Partial $\eta^2=0.25$) and internal rotation ($F(1,21)=33.825$, $P<0.001$, Partial $\eta^2=0.62$). Multivariate analysis for percent change revealed there was a significant multivariate group effect ($F(3,19)=4.224$, $P=0.019$, Partial $\eta^2=0.40$) for the 3 shoulder strength measures. Univariate analysis showed there was a significant difference between Train and Control for external rotation when the trained and untrained arms were pooled ($F(1,21)=10.097$, $P=0.005$, Partial $\eta^2=0.33$). Train means were 10.9% (SD 10.9) for training arm, and 12.7% (SD 9.6) for non-training arm, whereas Control means were 1.6% (SD 13.2) and -2.7% (SD 12.3) for trained and untrained arms, respectively (Figure 3.1). There was a significant difference between the groups for internal rotation with the trained and untrained arms pooled ($F(1,21)=5.425$, $P=0.030$, Partial $\eta^2=0.21$). Train means were 14.8% (SD 11.3) for training arm, and 14.6% (SD 10.1) for non-training arm, whereas Control means were 6.4% (SD 11.2) and 5.1% (SD 8.8) for trained and untrained arms, respectively (Figure 3.2). There were no significant differences for scaption, however significance reached $P=0.056$. Train means for scaption were 10.1% (SD 13.4) and 7.2% (SD 14.3), whereas Control means were 4.1% (SD 10.3) and -4.8% (SD 13.8) for trained and untrained arms, respectively (Figure 3.3). Raw

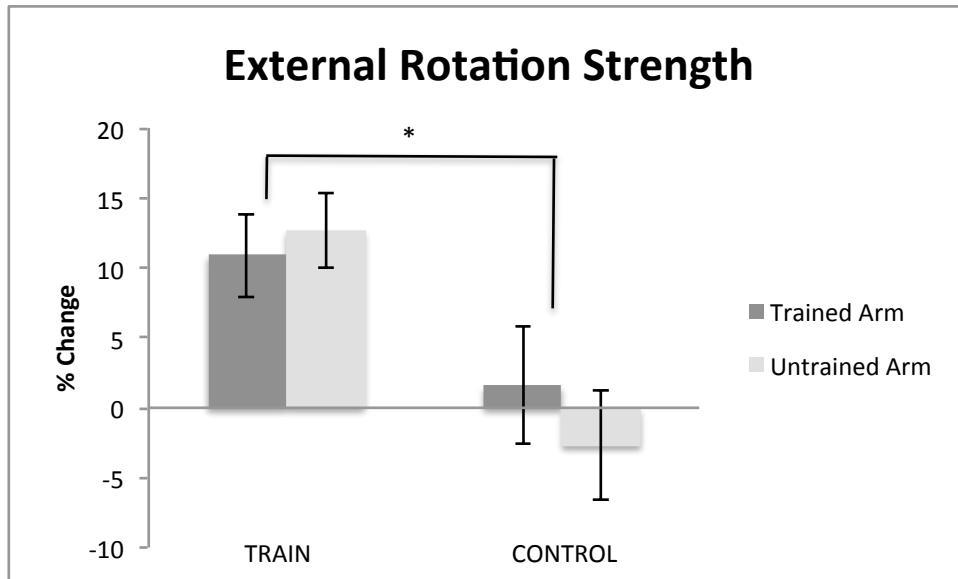


Figure 3.1 External rotation percent change in strength. Values are means \pm SE. Note that trained arm and untrained arm for Control were randomly selected. * Significantly different between Train and Control when pooled across arm ($P < 0.05$).

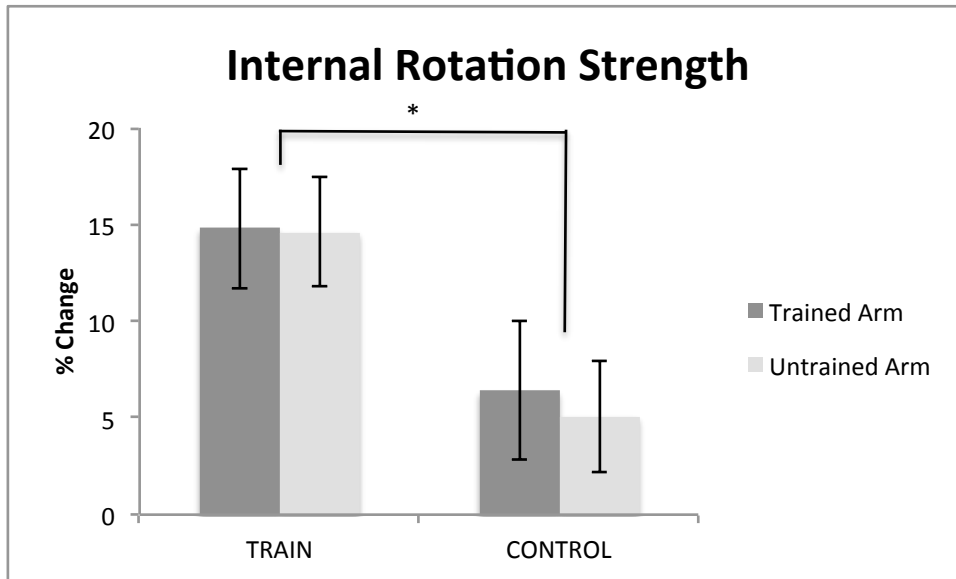


Figure 3.2 Internal rotation percent change in strength. Values are means \pm SE. Note that trained arm and untrained arm for Control were randomly selected. * Significantly different between Train and Control when pooled across arm ($P < 0.05$).

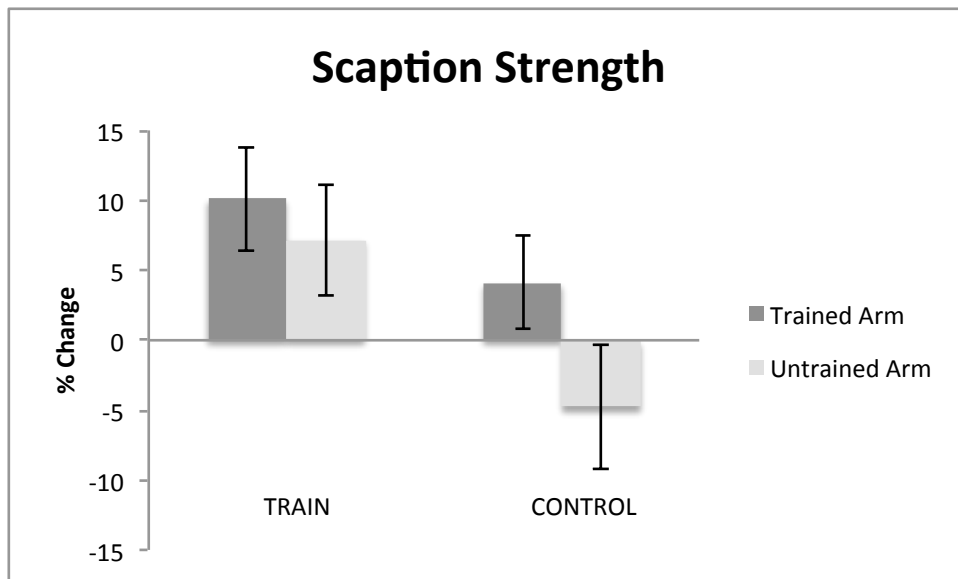


Figure 3.3 Scaption (abduction of the extended arm in the scapular plane, 30 degrees anterior from the coronal plane) percent change in strength. Values are means \pm SE. Note that trained arm and untrained arm for Control were randomly selected. No significant differences between Train and Control were detected ($P=0.056$)

Table 3.2 Raw scores for external rotation, internal rotation, scaption and handgrip strength. Values are means (\pm SD).

	External Rotation (kg)				Internal Rotation (kg)			
	Trained Arm		Untrained Arm		Trained Arm		Untrained Arm	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Train	12.0 (3.3)	13.4 (4.1)	11.9 (3.4)	13.4 (3.5)	16.3 (6.0)	18.4 (6.0)	16.1 (5.6)	18.1 (5.9)
Control	12.7 (4.3)	13.1 (5.1)	12.6 (3.8)	12.1 (3.6)	17.6 (6.8)	18.4 (7.0)	17.5 (6.8)	18.0 (6.3)
	Scaption (kg)				Handgrip (kg)			
	Trained Arm		Untrained Arm		Trained Arm		Untrained Arm	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Train	9.9 (3.6)	10.8 (3.7)	9.9 (3.5)	10.4 (3.3)	36.5 (10.9)	37.6 (10.7)	37.4 (11.0)	38.4 (10.2)
Control	11.6 (4.5)	12.1 (5.2)	11.0 (3.9)	10.5 (4.4)	44.3 (15.4)	44.5 (16.2)	42.3 (13.5)	43.0 (13.6)

Note: Control did not conduct any strength training. Left and right arm were randomized for trained arm and untrained arm in Control. There was a significant multivariate group X time interaction for the three shoulder tasks (external rotation, internal rotation and scaption).

Table 3.3 Raw scores for supraspinatus and anterior deltoid muscle thickness. All values are means (\pm SD).

	Supraspinatus (cm)				Anterior Deltoid (cm)			
	Trained Arm		Untrained Arm		Trained Arm		Untrained Arm	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Train	1.90 (0.32)	1.99 (0.31) *	1.86 (0.33)	1.85 (0.33)	1.08 (0.37)	1.21 (0.39) *	1.10 (0.36)	1.16 (0.34)
Control	2.15 (0.48)	2.14 (0.46)	1.99 (0.32)	2.00 (0.33)	1.34 (0.52)	1.26 (0.44)	1.36 (0.44)	1.26 (0.35)

Note: Control did not conduct any strength training. Left and right arm were randomized for trained arm and untrained arm in Control. * Significant difference between pre and post in Train (unadjusted results) ($P < 0.05$). When Bonferroni adjusted, Anterior Deltoid significance remains ($P < 0.0125$).

data for external rotation, internal rotation and scaption strength are shown in Table 3.2. For handgrip strength, there was a significant time main effect ($F(1,21)=6.317$, $P=0.020$, Partial $\eta^2=0.23$). This revealed that pooled across arm and group there was a significant difference between pre and post. Percent change analysis for handgrip strength revealed no significant differences. Train means were 3.6% (SD 6.1) and 3.7% (SD 6.6), Control means were 0.0% (SD 4.9) and 2.1% (SD 6.7) for trained and non-trained arms, respectively. Raw data for handgrip strength is shown in Table 3.2.

3.3.2 Muscle Thickness

There were no significant differences between groups at baseline for supraspinatus or anterior deltoid muscle thickness. The multivariate analysis revealed a significant group X time X arm interaction ($F(2,20)=4.407$, $P=0.026$, Partial $\eta^2=0.31$). Post hoc analyses revealed there were significant differences in Train only. Unadjusted results showed a significant difference between pre ($1.90 \pm 0.32\text{cm}$) and post ($1.99 \pm 0.31\text{cm}$) in the training arm for the supraspinatus muscle ($t(12)=-2.369$, $P=0.035$), and a significant difference between pre ($1.08 \pm 0.37\text{cm}$) and post ($1.21 \pm 0.39\text{cm}$) for anterior deltoid in the training arm ($t(12)=-4.898$, $P<0.001$). When Bonferroni adjustments were made the significant difference between pre and post for the anterior deltoid in the training arm remained ($P<0.0125$). There were no other significant different differences detected. Muscle thickness data are shown in Table 3.3.

3.4 Discussion

The main purpose of this study was to determine if an at-home strength training program using resistance tubing could produce increases in strength in both the trained and untrained shoulders. We found significant increases in the trained and untrained arms for external and internal rotation (Figures 3.1 & 3.2). For external rotation the trained arm increased 10.9%, whereas the untrained arm increased 12.7%. For internal rotation the trained arm increased 14.8%, whereas the untrained arm increased 14.6%. Interestingly, for both exercises, the increase in strength for the untrained arm was similar to that of the trained arm. On average, the strength gain from the trained to untrained limb is ~50% (Carroll et al., 2006); therefore our data demonstrates strength transfer exceeding the average effect. The large increase in strength in the untrained limb may be due to the training volume of the exercises. Typically, cross-education studies show increases in strength after training with one exercise; however, the training program in the present study consisted of five exercises. The novel nature of the exercises could have also contributed to the large increase in strength in the untrained limb (i.e. equal to or greater than the trained limb). Cross-education literature suggests there is greater transfer when exercises are more novel and involve more learning (Farthing, 2009). Although shoulder strength training exercises such as external and internal rotation using tubing are common in rehabilitation settings, they may be unique to untrained individuals and may involve much learning, therefore contributing to the large transfer of strength. These data suggest that the model of shoulder strength training on one limb using an at-home resistance tubing program can produce large cross-education effects to the opposite limb. To our knowledge, this is the first cross-education study to show that unilateral strength training can be transferred to the contralateral limb using shoulder exercises.

This study is also novel in being the first cross-education study to implement an at-home resistance tubing training program. Traditionally, cross-education research has been conducted in a supervised lab-based setting (Kannus et al., 1992; Hortobagyi et al., 1997; Farthing & Chilibeck, 2003; Farthing et al., 2005; Munn et al., 2005; Dragert & Zehr, 2011; Hortobágyi et al., 2011; Latella et al., 2012). The present study showed a significant increase in strength in two (external rotation and internal rotation) of the three shoulder exercises. Since cross-education literature is moving towards more rehabilitation based research, it is important to determine if more therapeutically relevant exercise programs, such as those using resistance tubing, can show increases in strength in both the trained and untrained limb. The findings from this study are needed to move towards applying cross-education into a real injury setting, where lab-based or supervised training programs are not feasible for a wide range of participants.

Scaption training did not show significant increases in cross-education compared to control. Train had a 10.1% increase in the trained arm and a 7.2% increase in the untrained arm compared to 4.1% and -4.8% in Control (Figure 3.3). We predicted that all shoulder tubing exercises would generate large cross-education effects due to the novel nature of the tasks, particularly scaption. It is possible that participants performed the scaption exercise incorrectly, or did not follow the exercise program to failure as they felt it was the most difficult exercise to conduct. Performing scaption correctly requires the surrounding muscles to stabilize the scapula. When participants execute this exercise, compensation techniques may be used if the surrounding muscles are not able to adequately stabilize the scapula. However, it should be noted that the change in scaption strength approached significance ($P=0.056$), whereby Train showed a trend for an increase in strength.

The training arm in Train showed significant increases in muscle thickness for the supraspinatus and anterior deltoid after 4-weeks. The supraspinatus increased approximately 5%, whereas the anterior deltoid increased approximately 12% (Table 3.3). The strength training program targeted the anterior deltoid as well as the muscles of the rotator cuff, including the supraspinatus. These changes are consistent with other unilateral strength training studies showing increased muscle size after a 4-week (Magnus et al., 2010) and 6-week (Farthing et al., 2005) strength training program. Importantly, the results may suggest that an at-home tubing exercise program could be effective for inducing hypertrophy. There was no change in muscle thickness for the untrained arm in Train, and there were no changes in either arm for Control (Table 3.3). The increase in muscle size for the training arm in Train may demonstrate that the increase in strength is in part due to the increase in muscle size. Therefore, it could be argued that the relative contribution of neural factors to the increase in strength was greater for the untrained limb (Farthing, 2009). However, since the purpose of this study was not to determine mechanisms, we did not take any neurophysiological measures (i.e. electromyography) and we can only speculate the contribution of neural factors to the increase in strength of the untrained limb.

The benefit of cross-education training for the function of the trained limb is also clinically relevant. If a unilateral training program were applied in a clinical setting (i.e. after shoulder surgery), the increase in muscle size of the trained limb may help maintain or improve the normal function of the healthy limb. Typically after an injury, the overall activity of the individual declines; therefore training the healthy limb may help preserve muscle size and strength of both the healthy and injured limb so overall weakening does not occur. Cross-education training may be beneficial not only after shoulder surgery, but between the time of the

injury to the time of surgery. Normally after an injury occurs there is a waiting period until the time of the surgery, which could be months to years long. If the healthy limb engaged in strength training during this phase, it may improve function of the trained limb, with potential for beneficial effects to cross over to the untrained limb prior to the surgery. Cross-education is also not restricted to shoulder injuries, but could be beneficial to other unilateral injuries such as after wrist fractures, or surgeries of the lower limb.

One limitation to the present study is that we cannot be certain about compliance to the exercise program. Train was given a log to keep track of their exercises, and all participants showed that they completed all 12 of the strength training sessions. Train was also contacted one-week into the strength training program to ensure they were completing the exercises. The program was intentionally unsupervised, with exercises taught to the participants once at the baseline testing session. Perhaps greater training effects would have been shown if the program was supervised. However, our aim was to ensure this was an at-home program that would be similar to the type of program implemented in a real injury setting. Another drawback of the at-home training program is that we cannot be certain that participants did not train both limbs, enhancing the cross-education effect. We interpret the lack of any evidence of muscle hypertrophy in the untrained limb of the training group as a clear indication that the unilateral training program was adhered to.

One concern when using resistance tubing to strength train is the ability to ensure the resistance is continually increasing as the participant progresses throughout the training program. When using dumbbells for example, it is very easy to determine increased load by recording the weight (i.e. in kg). With tubing, it is much more difficult to measure the resistance as it varies with changing the tubing length. In the current study, each training participant was given four

tubes, each of a different color, representing four different levels of resistance. The resistance tubes ranged from light exercise for beginners, to heavy exercise for trained athletes. Train was instructed to complete each set to failure, and was taught how to increase resistance either by using the same tube and modifying the length, or by changing tubes to the next highest resistance. Although it is difficult to measure the exact resistance with tubing, we ensured Train was increasingly loading their muscles by using the Borg CR10 Scale of Rated Perceived Exertion to record the difficulty of each set. The Borg CR10 scale has previously been shown to be useful in estimating exercise intensity in rehabilitation protocols (Andersen et al., 2010). The training program was essentially self-monitored by the participants, whereby they recorded the number of repetitions for each set and the colour of tubing; however, we cannot be certain that progressive overload was effectively achieved.

Another limitation to the present study is that if cross-education rehabilitation can be used in an injury setting, it may only be applicable to those who have a unilateral injury. If someone had a bilateral injury or a chronic condition on the less affected side, they likely would not be able to complete a strength training program. Although cross-education is only applicable in unilateral injuries, it has potential to improve the rehabilitation from injuries affecting one side of the body.

In conclusion, our data suggests that an at-home resistance tubing strength training program on one shoulder can produce increases in strength on both shoulders. This research may be feasible to implement into a rehabilitation model where a real injury has occurred, such as after shoulder surgery. The clinical applicability of these results should be taken with caution since this research was not conducted on injured participants. If implemented in a rehabilitation program, it is recommended that cross-education training be used in addition to the current

rehabilitation, not as a replacement. Together with previous work on cross-education effects to an immobilized limb (Farthing et al., 2009; 2011), this study represents an important step in understanding the potential clinical utility for rehabilitation after unilateral injuries; however more research is needed in an actual injury setting.

3.5 Relation of Experiment 2 to Thesis

The first objective of the thesis was to determine if cross-education could improve strength and functional performance of an immobilized limb using a shoulder sling model in both healthy and injured participants. The purpose of study two was to determine if an at-home resistance tubing strength training program on one shoulder would produce increases in strength in both the trained and untrained shoulders in healthy participants. In order to apply cross-education to unilateral shoulder injury settings, this study was needed to determine if a home-based training program was feasible to implement into an injury setting and to determine if the shoulder strength training program could significantly improve strength in the untrained limb.

Chapter 4: Experiment 3

4.1 Introduction

Cross-education is a neural adaptation defined as the increase in strength or functional performance of the untrained contralateral limb after unilateral training the opposite homologous limb (Farthing et al., 2005; Carroll et al., 2006). The increases in strength in the untrained limb are thought to be related to the gain in magnitude of the trained limb, and have been shown to reach 52% of the strength gained in the trained muscle (Carroll et al., 2006). Cross-education has consistently shown increases in strength in the untrained healthy limb by strength training the homologous muscle of the opposite limb; however, much less is known about the effects of cross-education in a real injury setting. If the phenomenon of cross-education is applied to unilateral limb immobilization after an injury (i.e. shoulder surgery) it may allow quicker recovery and may minimize the loss in function of the injured limb.

Four studies have applied cross-education to immobilization in non-injured participants (Farthing et al., 2009; Farthing et al., 2011; Magnus et al., 2010; Pearce et al., 2012). Farthing et al. (2009) used a unilateral limb immobilization model of forearm casting to immobilize healthy (i.e. non-injured) participants for 3 weeks. One immobilization group wore the forearm cast and strength trained the non-casted arm for 3 weeks, whereas the other immobilization group conducted no strength training. Results showed the non-training group decreased strength in the immobilized limb by 13%, and decreased muscle size by 4.2%, whereas the training group had no significant change in muscle size (0.8% decrease) or strength (2.1% increase) in the immobilized limb. Similarly, Magnus et al. (2010) applied cross-education to a healthy limb using an arm sling and swathe for 4 weeks. Results showed that strength training the non-immobilized limb attenuated the strength and muscle size loss of the immobilized limb. Pearce et al. (2012) replicated these findings by immobilizing healthy participants in a shoulder sling.

Results showed that for strength in the immobilized arm, the non-training group had a 19.9% decrease in strength, whereas the training group had a 0.6% decrease in strength. The study found that unilateral strength training of the non-immobilized limb maintained strength and muscle thickness of the immobilized limb. All three studies provide evidence for cross-education benefiting strength and muscle size after immobilization in non-injured participants. There has been only one study to date that has applied cross-education to a real injury setting (Stromberg, 1986; 1988) (reports from the same data set). In the Stromberg (1986; 1988) study, individuals with wrist/forearm injuries who strength trained the non-injured limb showed improved function in the injured limb compared to a non-training group. However, limitations such as not including raw data, not accounting for baseline differences, and not reporting details of the training program make it difficult to draw any conclusions from the results. More research needs to be conducted to determine if cross-education can benefit an injured limb, such as after rotator cuff surgery.

Rotator cuff pathology is one of the most frequent upper extremity disorders (Herberts et al., 1984). It typically results in loss of sleep, extensive pain, disruption in work, and difficulty in activities of daily living. Surgery is one of the most common treatments with primary goals of pain relief and functional improvement (Rokito et al., 1996). Although surgery has been shown to improve the condition (Kirschenbaum et al., 1993; Rokito et al., 1996; Cools et al., 2006; Holtby and Razmjou, 2010); evidence suggests that there are strength deficits ranging from 15 – 36% up to 6-8 months after the surgery (Binet et al., 2003), and satisfactory results after 1 year of rehabilitation (Rokito, 1999). Even after an average of 5 years post-surgery, a decline in strength still remains when compared to the non-operated extremity (Rokito, 1999). Similarly,

Bankart repairs are another common type of shoulder surgery that can take up to a year to fully recover strength (Rhee et al., 2007).

The standard rehabilitation protocol after shoulder surgery is immobilization in a sling, followed by the introduction of range of motion (ROM) exercises and basic strength restoration (Millett et al., 2006; Conti et al., 2009). For rotator cuff surgery, intermediate strength and stability training begins at 3-months post-surgery, and advanced strength training begins at 4-6 months post-surgery (Millett et al., 2006; Conti et al., 2009). In Bankart repairs, intermediate strength training begins at 2-3 months post-surgery and advanced strength training begins at 3-6 months post-surgery. It is important to note that the consensus in the literature is to focus rehabilitation entirely on the surgical side (Conti et al., 2009). To our knowledge, there is currently no formalized strength training program given to patients on the non-surgical side after surgery. The implementation of a strength training program on the non-surgical limb after surgery may benefit the rehabilitation of the surgical limb via cross-education. However, in a clinical setting a training program initiated after surgery should be feasible for post-surgery patients and clinically relevant. Therefore, exercises may have to be completed at home, without direct supervision, and without expensive equipment.

The purpose of the study was to apply a clinically relevant shoulder strength training program (used in Experiment 2 of the Ph.D. thesis) to unilateral shoulder surgery participants, and determine if cross-education training can improve strength, muscle thickness, active range of motion (AROM), and self-reported function of the surgical limb. The hypotheses are that unilateral strength training of the non-surgical limb plus standard rehabilitation of the surgical limb will improve strength, muscle thickness, AROM, and self-reported function of the surgical

limb compared to standard rehabilitation alone. This research has the potential to make advances in the current clinical rehabilitation protocols following rotator cuff surgery.

4.2 Methods

4.2.1 Participants

Males and females aged 18 and older on a shoulder surgery waiting list were recruited from an orthopaedic surgeon clinic in Saskatoon, Saskatchewan, Canada. Patients who were referred to the clinic that met the inclusion criteria were invited to participate in the study prior to their shoulder surgery. Those who were eligible for the study were initially screened by administrative staff and were asked if they were interested in taking part in a research study. If interested, potential participants were contacted via a phone call by the primary researcher. The orthopaedic surgeons were not informed which of their patients were involved in the study; and therefore remained blinded. Patients who were scheduled to receive unilateral rotator cuff surgery of any severity on either limb were recruited for the study. After recognizing low enrolment and recruitment challenges, Bankart repair surgery patients were also recruited. The purpose of rotator cuff surgery is to restore muscle balance with sufficient glenohumeral stability to improve shoulder function (Favard et al., 2007), whereas the purpose of Bankart repair surgery is to restore shoulder stability by re-attaching the torn ligament of the labrum to the glenoid neck (Randelli et al., 2012). Rotator cuff surgery patients are typically immobilized for 4 to 6 weeks, whereas Bankart repair surgery patients are typically immobilized for 4 weeks. There were a total of 15 participants who had rotator cuff surgery and 4 participants who had Bankart surgery (Table 4.1). Three orthopaedic surgeons were responsible for completing the surgeries for all participants. Exclusion criteria included any prior upper body injury or surgery

interfering with normal daily function on the non-surgical limb or any work-related or motor vehicle insurance claim made by the participant as a result of the shoulder injury.

Nineteen participants with an average age of 53.7 (\pm 17.5 years), height of 174.7 (\pm 8.0 cm) and weight of 85.7 (\pm 16.1 kg) were included in the study (Table 4.1). A sample size calculation was completed using G Power 3.2.1 (Faul et al., 2009). Based on previous data from pilot work using our shoulder strength measure, and literature to determine normal decreases in strength after rotator cuff surgery, it was anticipated that there would be a 10% difference in surgical limb strength between Train and Control at 3 months post-surgery. Using α of 0.05 at 80% power, it was predicted that 17 participants per group were needed (34 total). A dropout rate of 21% was predicted (based on the dropout rate in the wrist fracture study; study 4 in the thesis); therefore, a total sample size of 21 participants per group (42 total) was the projected need. A total of 20 participants were recruited for the study. One participant dropped out after the pre-surgery testing session; therefore, 19 participants were included in the final data analysis (See Figure 4.1 for the participant flow diagram).

Prior to commencement of the study, all participants signed informed written consent approved by the Biomedical Ethics Review Board at the University of Saskatchewan (see Appendix B for Certificate of Approval). All participants completed the Waterloo Handedness Questionnaire (WHQ) to determine handedness. The WHQ is scored from -20 to +20, where negative scores indicate left-handedness, and positive scores indicate right-handedness. There were 18 right-handed participants, and 1 left-handed participant. The means of the handedness scores are shown in Table 4.1. Resistance training experience in the past year was self-reported

Table 4.1 Participant descriptive statistics for each experimental group. Values are means (\pm SD).

	Age	Height (cm)	Weight (kg)	WHQ	Immob Period (days)	Time to Surgery (months)	# Cortisone Shots	Train Exp (months)	Type of Injury	Side of Surgery
Train (n=9)	49.0 (19.3)	176.2 (6.9)	87.5 (10.0)	14.8 (6.8)	38.0 (7.3)	20.6 (22.4)	1.6 (2.6)	4.3 (5.0)	6 RC 3 BK	6 D 3 ND
Control (n=10)	58.0 (15.6)	173.4 (9.0)	84.1 (20.5)	16.6 (4.6)	37.2 (7.1)	19.6 (16.0)	0.9 (2.5)	1.1 (2.0)	9 RC 1 BK	9 D 1 ND

Note: Abbreviations are as follows: Waterloo Handedness Questionnaire (WHQ), Immobilization (Immob), Experience (Exp), Rotator Cuff (RC), Bankart (BK), Dominant (D), Non-Dominant (ND). Training Experience was determined over the 12 months prior to the initial testing session. There were no significant differences between groups for any participant descriptives.

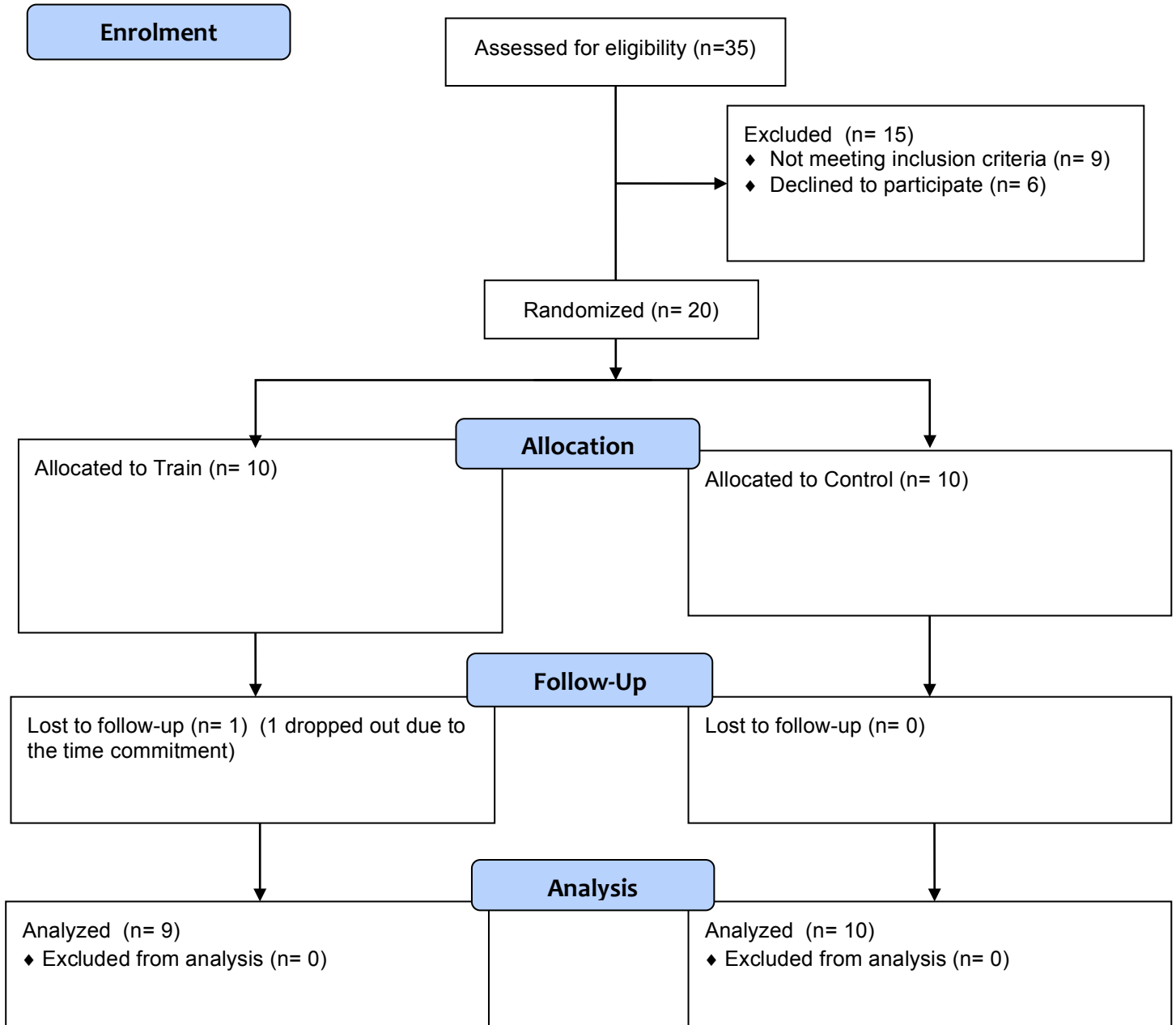


Figure 4.1 Participant enrolment flow diagram. Final n for Train =9. Final n for Control =10.

(in months) by the participants, whereby 1 month of resistance training consisted of strength training a minimum of 3 times/week for 4 weeks. All participants were asked to maintain their normal daily lifestyle throughout the study, with the exception of the limitations brought on by the shoulder sling. All participant descriptive statistics are shown in Table 4.1. There were no significant differences between groups for any of the participant descriptives.

4.2.2 Design

The design of the study was a between-within (mixed) design. Dependent measures were strength (external rotation, internal rotation, scaption, and handgrip), muscle thickness (supraspinatus, and anterior deltoid), AROM (external rotation and scaption) and the Western Ontario Rotator Cuff (WORC) Questionnaire (American Academy of Orthopaedic Surgeons, 1998). Pain was measured as a descriptive during all strength tests on the surgical arm as it has previously been shown to influence strength post shoulder surgery (Gerber et al., 2007). All participants had shoulder surgery resulting in immobilization and were randomized using a computer random number generator to one of two groups: Train or Control. Train had 9 participants (7 males, 2 females) and Control had 10 participants (6 males, 4 females). Train completed the standard rehabilitation program as delivered by their orthopaedic surgeon and physiotherapist, plus they conducted a unilateral shoulder strength training program on the non-surgical arm. Control completed the standard rehabilitation program from their orthopaedic surgeon and physiotherapist, but had no strength training intervention on the non-surgical arm. The standard rehabilitation protocol after rotator cuff surgery from the orthopaedic surgeon clinic was to immobilize in a sling for 4-6 weeks, begin passive ROM in the first 6 weeks and progress towards moving in forward elevation and external rotation. From 6-12 weeks promote active

ROM and initiate basic strength exercises such as postural/scapular control activities, submaximal isometrics, wall presses, and light exercise tubing. From 12-16 weeks promote continued ROM and begin intermediate strengthening and dynamic stability restoration. At 16-24 weeks progress to advanced strengthening and specific sport or work programming. The standard rehabilitation protocol after Bankart repair surgery from the orthopaedic surgeon clinic was to immobilize in a sling for 4 weeks, promoting elbow, wrist and finger movement and to begin ball squeezes. From 4-8 weeks promote gradual increased passive and active ROM into elevation and external rotation. Promote basic strength restoration with activities such as postural/scapular control activities, submaximal isometrics, scapular plane elevation, and introduce light resistance tubing and light dumbbells. From 8-12 weeks promote continued ROM and intermediate strength and dynamic stability restoration. From 12-24 weeks progress to advanced strength and include specific sport or work programming. All participants followed the rehabilitation program specific to their surgery from their orthopaedic surgeon; however, the rehabilitation programs from the physical therapists varied on an individual basis. All physiotherapy programs focused on improving ROM and strength, but the specific exercises, the duration of the exercises, and the repetition timing for exercises was not consistent across participants.

Participants were tested at four separate time points: pre-surgery, 6 weeks post-surgery (i.e. upon removal of the sling), 3 months post-surgery, and 6 months post-surgery. At pre-surgery, 3 months post-surgery, and 6 months post-surgery participants were tested for all measures on each arm. As recommended by the surgeons, shoulder strength testing after the surgery was not permitted on the surgical shoulder until 3 months post-surgery, therefore external rotation, internal rotation, and scaption strength was not assessed at 6 weeks post-

surgery. Handgrip strength was tested at 6 weeks post-surgery, as it did not directly affect the shoulder.

4.2.3 Strength Training Intervention

Strength training was conducted at home on the non-surgical arm only. Participants were instructed to begin the training program within 2-weeks post-surgery and commenced when they felt well enough after recovering from the surgery. The training duration was 6 months and was conducted 3 times per week. Participants were instructed to leave a day rest between training sessions. Training participants needed to complete a minimum of 2 training sessions per week on average to be considered trained and included in the final analysis. All training participants were contacted every 2-weeks to ensure they were compliant with their exercises, and to see if they had any questions regarding the training program, including progressions in training. To limit the effect of the contact between the researcher and the participant, Control was also contacted every 2-weeks and was asked how their surgical shoulder was feeling, and if there were any changes since the last contact was made.

The strength training program implemented in Experiment 2 of the Ph.D. thesis (refer to chapter 3) was used in the present study, and consisted of both dynamic and isometric sets for the following exercises: external rotation, internal rotation, scaption, flexion, and retraction. These exercises were chosen in consultation with the physiotherapists and were designed to adequately strengthen all muscles surrounding the shoulder. Dynamic exercises were used to replicate resistance tubing strength training commonly used in rehabilitation settings, and isometric exercises were used for specificity to the isometric exercise testing. The strength training program was progressive, beginning with 1 set of dynamic and 1 set of isometric exercises for

each movement. After one week, training progressed to 2 sets of dynamic and 2 sets of isometric exercises for each movement and remained this way until the last week of the training program. In the last week of the program, the training load was reduced to 1 set dynamic and 1 set isometric for each exercise to serve as a taper. Participants were instructed to complete all dynamic exercises through the full ROM to the best of their ability and were instructed to complete 10-15 repetitions to failure for each set. One-minute rest was left between each set.

Four different resistance tubes with handles (Leonard Fitness Inc., China, Workoutz.com), and progressively increasing levels of tension, were given to each training participant. The level of tension was coded by different colors beginning with yellow for light exercise and beginners (1.8-2.3 kg resistance), red for medium to heavy exercise (4.1-4.5 kg resistance), blue for moderately trained individuals (5.5 kg resistance), and black for trained athletes (7.3 kg resistance). A Canadian Society for Exercise Physiology - Certified Exercise Physiologist (CEP) taught the exercises to participants in the training group at the pre-surgery testing session, and the program was conducted unsupervised at home. The dynamic exercises were completed for 2-seconds in the concentric phase of the contraction, and 2-seconds in the eccentric phase of the contraction while using the appropriate exercise tube to maintain resistance throughout the contraction. Static exercises were held for 3-seconds and were completed using the strongest tube (black) to hold the contraction in the desired position. The position for static exercises was the same position the strength testing was completed in for external rotation, internal rotation, and scaption (refer to the Strength Testing section below). The hold position for flexion was 20 to 30 degrees away from the body and the position for retraction was at the end of the movement with the elbow flexed. The training group was instructed to complete each set to failure, and was taught how to increase resistance either by using the same tube and modifying the length, or by

changing tubes to the next highest resistance. Participants were also instructed to relax the non-training limb during the training to limit any mirror activity of the non-trained limb.

The Borg Scale of Rating of Perceived Exertion (Borg CR10) (Borg, 1998) was used after each training session to gauge the difficulty of the exercises. The Borg CR10 scale has previously been shown to be useful in estimating intensity of exercises in individual rehabilitation protocols (Andersen et al., 2010). Participants were instructed to work in the 5-10 range (strong to very, very strong) of the scale to ensure the exercises remained challenging. A training log was used to record the repetitions for each set and the difficulty of each exercise.

4.2.4 Strength Testing

Maximal isometric shoulder strength (kg) (external rotation, internal rotation, and scaption) was assessed on both arms using a hand-held dynamometer (Lafayette Manual Muscle Test System, Lafayette Instrument, Lafayette IN). Hand-held dynamometry was chosen, as it is portable, clinically relevant, and is valid and reliable (Bohannon, 1986; Sullivan et al., 1988; Magnusson et al., 1990). The hand-held dynamometer also provided more freedom of movement and testing range for shoulder strength, is much more cost effective, and is feasible in a large, high volume clinical setting. The coefficient of variation for the hand-held dynamometer was found to be 4.5% for external rotation, 4.3% for internal rotation, and 4.4% for scaption using a separate sample of 10 participants. These precision scores are consistent with the range of values previously reported for isokinetic dynamometry in our lab (Farthing et al., 2005).

The same methods for testing shoulder strength in Experiment 2 of the Ph.D. thesis were used in the present study (see Appendix C for pictures of strength testing positions). Shoulder strength of the surgical shoulder (external rotation, internal rotation, and scaption) was assessed

pre-surgery, 3 months post-surgery, and 6 months post-surgery. Strength of the non-surgical shoulder was also assessed at 6 weeks post-surgery. The three shoulder motions were tested in a seated position with the feet flat on the floor. The dynamometer was placed just above the wrist (proximal to the ulnar styloid process) (Reinold et al., 2008). For external and internal rotation, the elbow was bent at 90 degrees with the shoulder at 0 degrees of abduction. The elbow rested alongside the participant's body with the forearm anterior to the body and the hand in neutral position (palm facing medially). Scaption was tested with 0 degrees of flexion at the elbow. The arm was abducted 20 degrees from the body, and 30 degrees anterior from coronal plane of the body. The wrist was in neutral position with the palm facing down. The motions of external rotation, internal rotation and scaption were chosen as outcome measures of strength because they are clinically relevant to shoulder injuries such as rotator cuff tears. Two additional strength training exercises (retraction and shoulder flexion) were included in the training program but not in the strength testing for feasibility; additional strength testing measures would increase the total time commitment of participants, as well as increase fatigue of the shoulder muscles during the testing. The contractions were 3-seconds long to match the 3-second static contractions completed in the strength training program. The best of 3 repetitions was recorded as the peak torque (kg). Participants were instructed to progressively increase force within each individual contraction so they reached maximal force at the end of the 3-seconds. In the event that the body position of the participant moved, additional repetitions were performed. The order of testing was the same for all participants (external rotation, followed by internal rotation, scaption, and then handgrip). The non-surgical arm was always tested first, followed by a minute rest between each testing round. Participants were familiarized to the strength testing procedures prior to completing the testing to limit any learning effects.

Handgrip strength (kg) was assessed on both hands using a handgrip dynamometer (JAMAR dynamometer, JA Preston Corp., Jackson, MI) in the seated position with the elbow bent at 90 degrees. This position was chosen because it is the testing position used in most clinical settings and is recommended by the American Society of Hand Therapists (Innes, 1999). Handgrip strength was assessed to provide a global estimate of upper body strength for both groups. Handgrip contractions were 3-seconds long with the best of 3 repetitions used as the peak. Handgrip strength was assessed at all testing time points (pre-surgery, 6 weeks, 3 months, and 6 months post-surgery). Verbal encouragement was given for all strength testing measurements.

Pain was measured after each repetition for all strength exercises on the surgical arm using a visual analog scale (VAS) (Cho & Rhee, 2009). The VAS was used to measure pain during the contraction with 0 indicating no pain, and 100 indicating extreme pain. Participants marked their pain during the contraction with a slash on the VAS line (See Table 4.2 for pain scores in results section). Pain was measured as a potential confounding variable for strength.

4.2.5 Muscle Thickness

Muscle thickness of the supraspinatus and anterior deltoid (cm) was assessed at all testing time points (pre-surgery, 6-weeks, 3 months and 6 months post-surgery) using a portable US scanner (LOGIQ e BTO8, GE Healthcare) equipped with a linear (38.4 mm) 12 Hz transducer (resolution 0.3mm). The methods of Experiment 2 in the Ph.D. thesis for muscle thickness were used. Muscle thickness was used as an indicator to assess any changes in the muscle as a result of the training program. Ultrasound has previously been used in other studies to monitor changes in the muscle after strength-training interventions (Farthing et al., 2005; Farthing et al.,

2009; Magnus et al., 2010). The supraspinatus was chosen, as it is the rotator cuff muscle most commonly injured (Cofield et al., 2001), and is superficial to the skin surface; therefore, can easily be measured with ultrasound. The anterior deltoid was chosen, as it is a superficial shoulder muscle that is easy to access and view with ultrasound, and is a muscle that can easily be landmarked. The supraspinatus measurement was taken 4 cm medial to the most medial point of the acromioclavicular joint on the bulk of the muscle. The anterior deltoid landmark was located by placing the probe on the bulk of the muscle on the anterior aspect of the shoulder. The location was approximately 7 cm down from the uppermost point of the shoulder in line with the midpoint of the anterior deltoid. Both muscles were measured with the arm in a relaxed position, resting on the participant's lap. Sagittal images were taken with the ultrasound probe placed perpendicular to the muscle (See Appendix D for supraspinatus ultrasound image). Minimal pressure was applied to the probe to avoid deforming the underlying tissues.

Muscle thickness was assessed prior to any strength testing. Both shoulders were measured with a stringent land-marking method using an overhead transparency film to ensure an identical location at each testing point (Farthing & Chilibeck, 2003). The non-surgical arm was always measured first to ensure standardized timing of the procedure. At each location, four measurements were taken with the average of the closest two measurements used for comparison. Additional measurements were taken if any two of the four measurements were not within 1 mm to ensure precision. The coefficient of variation for ultrasound to assess muscle thickness was found to be 3.7% (average of supraspinatus and anterior deltoid) using a separate sample of 10 participants in our lab.

4.2.6 Active Range of Motion (AROM)

Active ROM was assessed manually using a Jamar goniometer by the primary researcher for shoulder external rotation, internal rotation, and supination. Manual goniometry has been previously shown to be reliable (intraclass correlation coefficient (ICC) ranging from 0.91 to 0.99) for shoulder flexion, external rotation and internal rotation (Mullaney et al., 2010). ROM was assessed at all testing time points (pre-surgery, 6 weeks, 3 months, and 6 months post-surgery). All three ROM measures were conducted with the participant seated and the feet flat on the floor. For external and internal ROM, the elbow was bent at 90 degrees with the shoulder at 0 degrees of abduction. The elbow rested alongside the participant's body with the forearm anterior to the body and the hand in neutral position (palm facing medially). For external and internal ROM, the stationary arm of the goniometer was placed 90 degrees perpendicular to the thorax of the body, in line with the quadriceps. The moving arm of the goniometer was kept in line with the forearm during the measurement. For external ROM, the forearm was moved in external rotation until the end active ROM or until the point of mild discomfort for the participant. For internal rotation, the forearm was actively moved internally until the end ROM or until the point of discomfort for the participant. Internal rotation ROM was found to not change in any participant (i.e. full ROM was achieved by every participant at each testing time point); therefore the data are not presented. Scaption ROM was tested with the arm at 0 degrees of flexion at the elbow and 30 degrees anterior from the coronal plane of the body. The wrist was in neutral position with the palm facing down. The stationary arm of the goniometer was kept in line with the lateral edge of the thorax and the moving arm was kept in line with the humerus. The participant's arm was moved anteriorly in the scaption plane until the end ROM or until the point of discomfort for the participant.

4.2.7 Western Ontario Rotator Cuff Questionnaire (WORC)

The WORC was measured to assess self-reported function. Permission was granted to use the WORC questionnaire (American Academy of Orthopaedic Surgeons, 1998) prior to its use in the present study. The WORC is a 21-item questionnaire designed to assess function of the rotator cuff and is a valid and reliable tool for assessing rotator cuff repairs (Kirkley et al., 2003). The questionnaire is split into five domains: physical symptoms, sports/recreation, work, lifestyle, and emotions. The WORC uses a VAS for all questions and is scored by measuring the distance from the left side of the line to where the participant marked their response on the line. The score range for each question is 0 to 100. An overall score for each domain can be calculated, as well as a total score for all domains added together (maximum score is 2100). The higher the score, the more symptomatic the participant is (i.e. a score of 2000 indicates an extremely symptomatic shoulder). The total score can also be converted to a percent of overall function, whereby a score of 0% indicates a dysfunctional shoulder, and a score of 100% indicates a totally functional shoulder (See Appendix E for the WORC Questionnaire). In the present study, the data for percentage of overall function is reported. The WORC questionnaire was assessed at every testing time point (pre-surgery, 6 weeks, 3 months, and 6 months post-surgery).

4.2.8 Data Analysis

All data were analyzed using SPSS 20.0 and checked for normality using skewness and kurtosis tests. Little's MCAR (Missing Completely at Random) test was used to determine that all strength tests (external rotation ($\chi^2(10)=9.113, p=0.521$), internal rotation ($\chi^2(10)=8.958, p=0.536$), scaption ($\chi^2(13)=18.526, p=0.139$), and handgrip ($\chi^2(17)=18.788, p=0.341$), were

MCAR. Supraspinatus ($\chi^2(12)=7.907, p=0.792$), and anterior deltoid ($\chi^2(12)=15.530, p=0.241$), muscle thickness was found to be MCAR, as well as external rotation ROM ($\chi^2(6)=4.675, p=0.586$), and scaption ROM ($\chi^2(6)=4.712, p=0.581$). The WORC questionnaire was also MCAR ($\chi^2(6)=7.016, p=0.319$). There was a total of 8/133 missing data points for external and internal rotation strength, 10/133 for scaption strength, 9/152 for handgrip strength, 8/152 for supraspinatus and anterior deltoid muscle thickness, 4/76 for external rotation ROM, scaption ROM and the WORC questionnaire. Group series means were used to replace all missing data (Tabachnick & Fidell, 2013).

Pain significantly correlated with strength for most strength measures, and specifically correlated with strength at baseline (R values for all significant correlations between pain and strength ranged from -0.576 to -0.467, $p<0.05$). However, an ANCOVA (analysis of covariance) could not be used because the covariate did not have the same relationship with strength across all time points and violated the homogeneity of regression assumption. The homogeneity of regression assumption states that the relationship between the dependent variable and the covariate is equal for all levels (i.e. the slopes are equal for all cells) (Tabachnick & Fidell, 2013). The relationship between pain and strength was not equal for all levels; therefore the analysis was not valid. Since baseline differences existed between groups for strength (and was related to the pain scores), percent change back to the non-surgical limb was used to account for these potential confounds since ANCOVA was not valid. All strength tasks (i.e. external rotation, internal rotation, scaption, and handgrip) were analyzed separately. Arms (i.e. non-surgical and surgical) were also analyzed separately due to the different time points for each arm (i.e. non-surgical was tested at pre-surgery, 6 weeks, 3 months, and 6 months; surgical was tested at pre-surgery, 3 months and 6 months). Percent change in strength was calculated for both non-

surgical and surgical arms using the non-surgical arm as the baseline (i.e. pre-surgery) testing point. Although the surgical arm was tested at pre-surgery, the surgical arm pre-surgery values were not used as the baseline due to the variability in the strength scores. The primary researcher also identified the surgical arm pre-surgery values as inaccurate due to participant's fear of re-injury prior to surgery. Raw data for all surgical and non-surgical strength values are shown in Table 4.3. Percent change for all strength measures was calculated by subtracting the respective post-surgery score from the non-surgical baseline score, dividing by the non-surgical baseline score, and multiplying by 100.

All strength analyses were conducted on percent change data. Non-surgical arm strength for external rotation, internal rotation, scaption and handgrip was analyzed using a Group (Train, Control) \times Time (6 weeks, 3 months, 6 months) repeated measures ANOVA (analysis of variance). Surgical arm strength for external rotation, internal rotation, and scaption was analyzed using a Group (Train, Control) \times Time (3 months, 6 months) repeated measures ANOVA. Handgrip strength for the surgical arm was analyzed using a Group (Train, Control) \times Time (6 weeks, 3 months, 6 months) repeated measures ANOVA since handgrip could be measured at 6 weeks post-surgery for the surgical arm. Planned comparisons using one-sample t-tests were conducted for all strength tasks to test the percent change in strength against zero, and were adjusted for multiple comparisons. Raw scores for muscle thickness of the supraspinatus and anterior deltoid were analyzed together using Group (Train, Control) \times Time (pre-surgery, 6 weeks, 3 months, 6 months) \times Arm (non-surgical, surgical) repeated measures MANOVA (multivariate analysis of variance). ROM for external rotation and scaption was analyzed together using a Group (Train, Control) \times Time (pre-surgery, 6 weeks, 3 months, 6 months) repeated measures MANOVA. The WORC was analyzed using a Group (Train,

Control) \times Time (pre-surgery, 6 weeks, 3 months, 6 months) repeated measures ANOVA. If significant main effects or interactions were detected, simple main effects analysis continued using one-way ANOVA and t-tests with Bonferroni adjustments made where appropriate. Bonferroni adjustments were made using SPSS programming where possible (identified by stating Bonferroni adjustments were made for multiple comparisons) or were adjusted for manually by dividing by the number of tests (i.e. $p < 0.05/3 = 0.017$). Significance was accepted at $p < 0.05$. Means and standard deviations of data are reported in text and tables. In figures, means and standard errors are reported to improve readability of the graphs.

4.3 Results

4.3.1 Strength

For non-surgical external rotation strength, there was Group main effect ($F(1,17)=15.10$, $p=0.001$). This revealed that there was a significant difference between groups pooled across time (6 weeks, 3 months, 6 months), favouring the training group (Bonferroni adjusted for multiple comparisons, $p < 0.05$). The one-sample t-tests showed that non-surgical external rotation strength for Train was significantly different than zero at 6 weeks ($9.5 \pm 7.2\%$), 3 months ($10.5 \pm 8.3\%$), and 6 months ($10.1 \pm 4.5\%$) (Bonferroni adjusted, $p < 0.05/3 = 0.017$). For surgical external rotation strength, there was time main effect ($F(1,17)=17.00$, $p=0.001$), which showed that pooled across groups, there was a significant difference in strength from 3 months to 6 months (Bonferroni adjusted for multiple comparisons, $p < 0.05$). One-sample t-tests showed that surgical external rotation strength for both Train ($-40.4 \pm 29.9\%$) and Control (-30.7 ± 20.5) were significantly different than zero at 3 months (Bonferroni adjusted, $p < 0.05/2 = 0.025$).

Table 4.2 Pain during strength tests for external rotation, internal rotation, scaption and handgrip. All values are means (\pm SD).

		Train	Control
External Rotation Pain	Pre-Surgery	34.9 (27.1)	56.6 (17.8)
	3 Months	32.4 (17.7)	24.2 (24.7)
	6 Months	25.5 (11.7)	16.9 (22.9)
Internal Rotation Pain	Pre-Surgery	24.8 (21.1) *	52.0 (23.3)
	3 Months	26.8 (22.5)	21.1 (23.9)
	6 Months	11.7 (11.7)	12.0 (18.4)
Scaption Pain	Pre-Surgery	42.9 (29.3)	62.8 (28.9)
	3 Months	38.4 (25.9)	31.4 (21.9)
	6 Months	24.5 (16.6)	18.0 (28.6)
Handgrip	Pre-Surgery	8.6 (15.2)	14.1 (17.7)
	6 Weeks	15.8 (11.8)	5.9 (6.5)
	3 Months	5.0 (5.6)	2.3 (2.5)
	6 Months	8.2 (7.3)	1.9 (3.2)

Note. Pain scores range from 0 (no pain) to 100 (extreme pain). * Significant difference between groups at pre-surgery ($p=0.017$, unadjusted). The pre-surgery difference between groups for external rotation was not significant; however, $p=0.053$. Refer to data analysis section for a description of how pain was accounted for in the analysis.

Table 4.3 Raw data for external rotation, internal rotation, scaption and handgrip strength (kg). All values are means (\pm SD).

		Non-Surgical				Surgical			
		Pre-Surgery	6 Weeks	3 Months	6 Months	Pre-Surgery	6 Weeks	3 Months	6 Months
External Rotation	Train	15.7 (3.7)	17.1 (3.5)	17.7 (2.9)	16.6 (2.9)	11.0 (3.8) *	-	8.9 (3.1)	12.2 (1.6)
	Control	12.5 (3.5)	11.7 (2.9)	11.8 (3.0)	11.8 (3.1)	7.4 (3.2)	-	8.4 (3.0)	10.0 (3.5)
Internal Rotation	Train	19.7 (7.1)	21.6 (6.1)	23.6 (6.0)	23.7 (5.9)	16.4 (4.5) *	-	15.9 (5.4)	20.2 (5.9)
	Control	16.3 (6.1)	16.4 (6.5)	17.0 (7.1)	17.0 (6.0)	11.0 (5.3)	-	13.3 (5.1)	16.3 (5.5)
Scaption	Train	11.8 (3.4)	12.2 (4.0)	13.7 (3.0)	12.5 (4.3)	7.4 (3.7)	-	6.4 (3.6)	7.8 (2.1)
	Control	9.1 (2.9)	9.8 (3.4)	9.7 (3.4)	9.7 (2.5)	4.6 (4.2)	-	5.2 (2.5)	6.9 (2.5)
Handgrip	Train	46.2 (12.8)	49.6 (11.4)	50.3 (12.6)	46.7 (9.6)	46.7 (12.3)	38.9 (9.3)	44.7 (10.1)	43.7 (9.9)
	Control	39.4 (10.5)	38.9 (10.8)	39.9 (10.4)	40.3 (10.6)	39.1 (9.0)	35.8 (9.2)	38.8 (9.1)	40.7 (9.8)

Note: Surgical arm at pre-surgery displays the actual pre-surgery surgical arm data. Raw data presented in the table is the data without group mean replacement of missing values; therefore the raw data does not exactly reflect the percent change figures. External rotation, internal rotation and scaption strength was not tested at 6 weeks on the surgical arm. All strength analyses were conducted on percent change data. * Significant difference between groups at pre-surgery (External Rotation $p=0.038$, unadjusted; Internal Rotation $p=0.029$, unadjusted). Refer to data analysis section for a description of how the significant baseline difference was accounted for in the analysis.

Percent change in external rotation strength for both arms is shown in Figure 4.2, and raw data are shown in Table 4.3.

For non-surgical internal rotation strength, there was a time main effect ($F(2,34)=6.37$, $p=0.004$) and a group main effect ($F(1,17)=7.43$, $p=0.014$). Post hoc analysis showed that there was a significant difference in strength between 6 weeks and 6 months, and 3 months and 6 months pooled across groups (Bonferroni adjusted for multiple comparisons, $p<0.05$). The group main effect revealed that there was a significant difference between groups pooled across time (6 weeks, 3 months, and 6 months), favouring the training group (Bonferroni adjusted for multiple comparisons, $p<0.05$). One-sample t-tests showed that non-surgical internal rotation strength for Train was significantly different than zero at 3 months ($13.6 \pm 12.9\%$) and 6 months ($35.6 \pm 26.5\%$) (Bonferroni adjusted, $p<0.05/3=0.017$). There was a time main effect for surgical internal rotation strength ($F(1, 17)=27.64$, $p<0.001$), showing that pooled across groups, there was a significant difference from 3 months to 6 months (Bonferroni adjusted for multiple comparisons, $p<0.05$). There were no significant differences for the one-sample t-tests in the surgical side for internal rotation. Percent change in internal rotation strength for both arms is shown in Figure 4.3, and raw data are shown in Table 4.3.

For non-surgical scaption there were no significant differences for the overall repeated measures ANOVA, and no significant differences for the one-sample t-tests. There was a significant time main effect for surgical arm scaption ($F(1,17)=10.36$, $p=0.005$). The time main effect revealed that there was a significant difference between 3 months and 6 months pooled across groups (Bonferroni adjusted for multiple comparisons, $p<0.05$). The one-sample t-tests for surgical scaption showed that Train was significantly different than zero at 3 months ($-46.3 \pm 33.9\%$), and Control was significantly different than zero at 3 months ($-40.4 \pm 23.3\%$) and 6

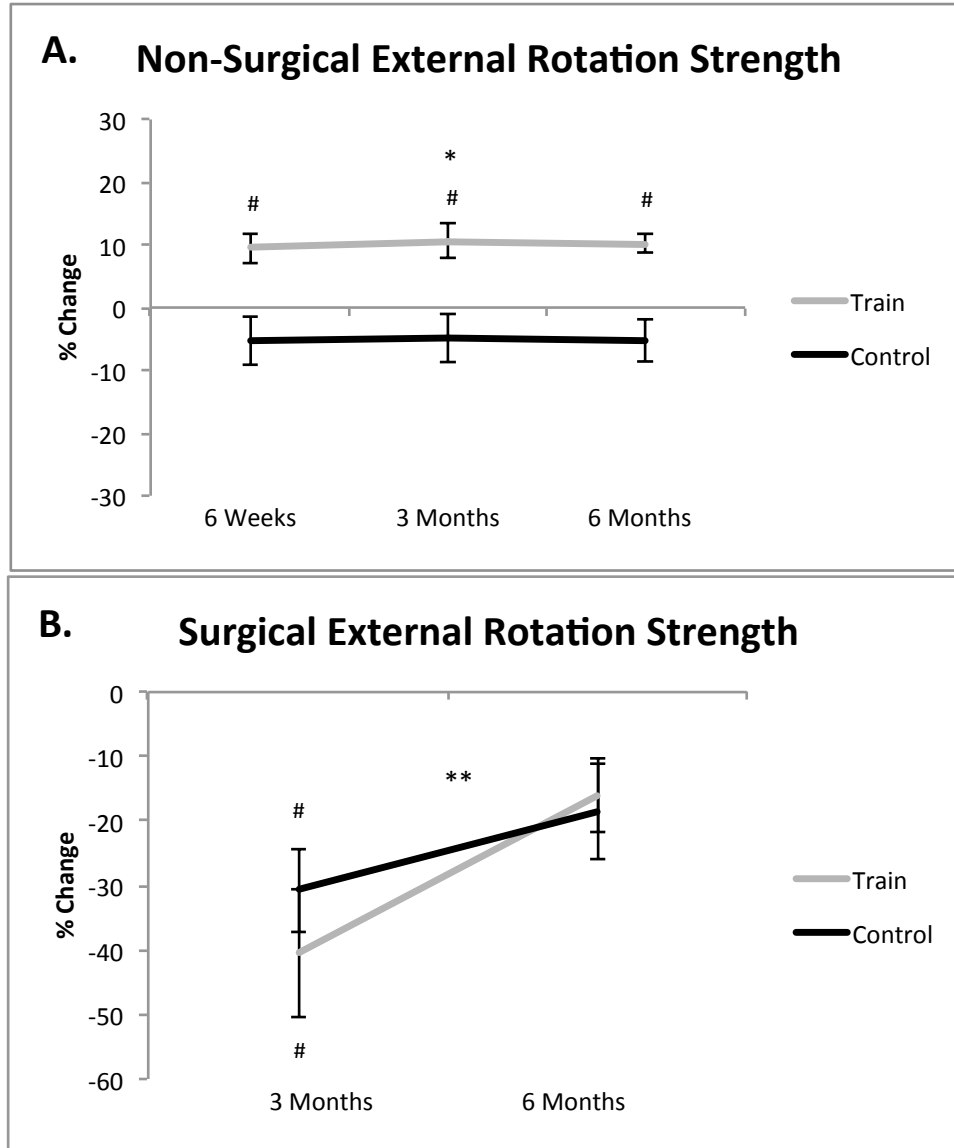


Figure 4.2 Percent change in external rotation strength. Values are means (\pm SE). Note: Surgical arm was not tested at 6 weeks for strength. A. Non-surgical arm percent change in strength. B. Surgical arm percent change in strength. * Significant difference between groups pooled across time (Bonferroni adjusted for multiple comparisons, $p < 0.05$). ** Significant difference from 3 to 6 months pooled across group (Bonferroni adjusted for multiple comparisons, $p < 0.05$). # Significantly different than zero (Bonferroni adjusted, $p < 0.05/3 = 0.017$ for non-surgical arm; $p < 0.05/2 = 0.025$ for surgical arm).

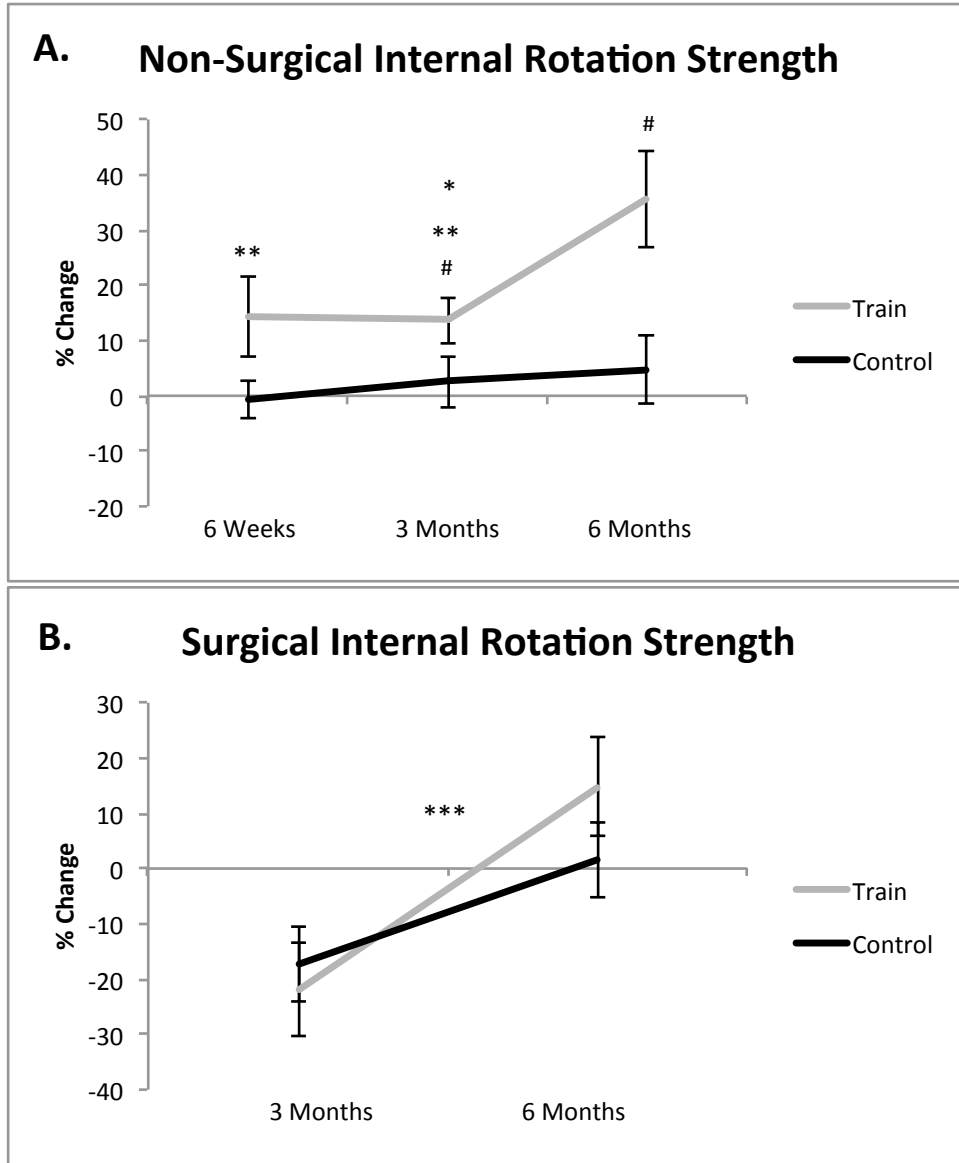


Figure 4.3 Percent change in internal rotation strength. Values are means (\pm SE). Note: Surgical arm was not tested at 6 weeks for strength. A. Non-surgical arm percent change in strength. B. Surgical arm percent change in strength. * Significant difference between groups pooled across time (Bonferroni adjusted for multiple comparisons, $p < 0.05$). ** Significantly different than 6 months pooled across group (Bonferroni adjusted for multiple comparisons, $p < 0.05$). *** Significant difference from 3 to 6 months pooled across group (Bonferroni adjusted for multiple comparisons, $p < 0.05$). # Significantly different than zero (Bonferroni adjusted, $p < 0.05/3 = 0.017$).

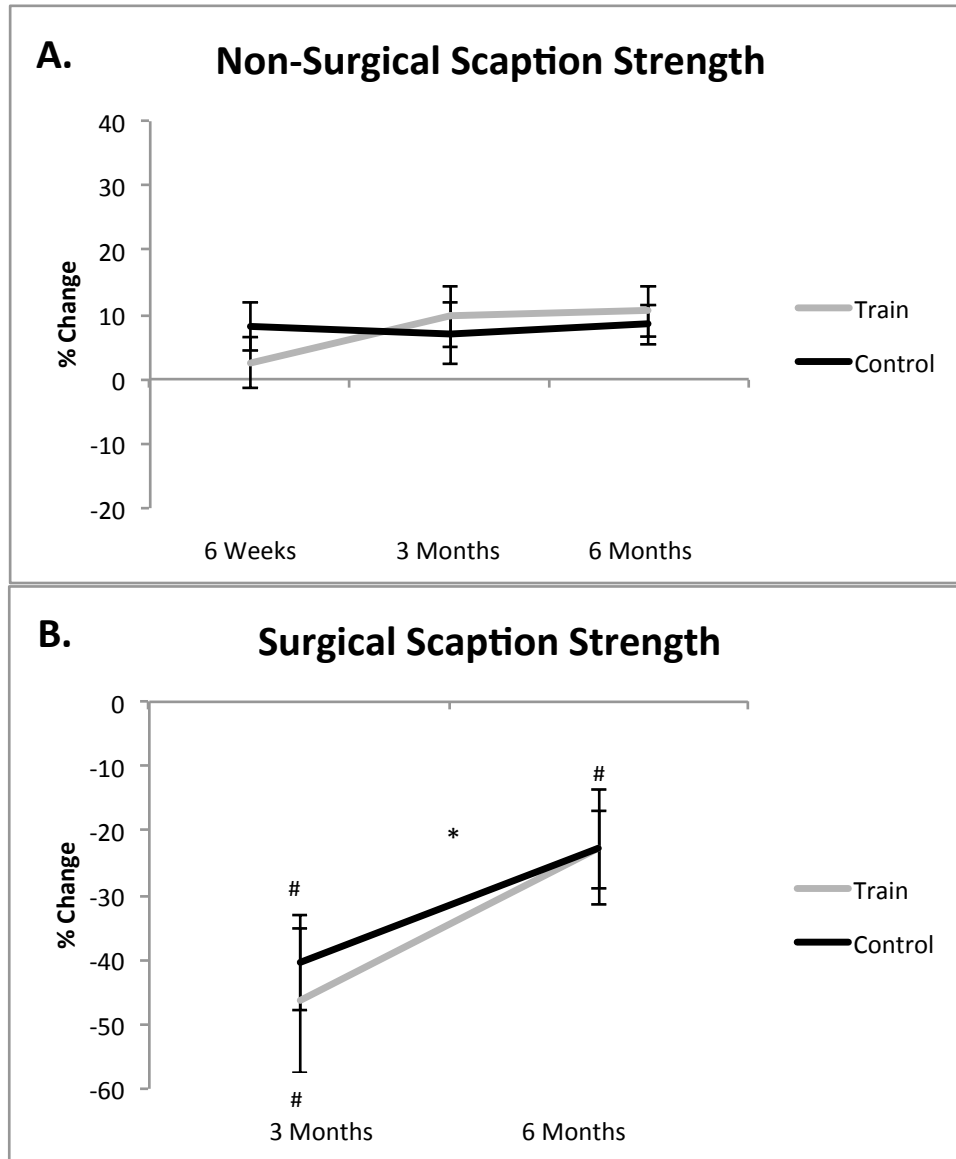


Figure 4.4 Percent change in scaption strength. Values are means (\pm SE). Note: Surgical arm was not tested at 6 weeks for strength. A. Non-surgical arm percent change in strength. B. Surgical arm percent change in strength. * Significant difference from 3 to 6 months pooled across groups (Bonferroni adjusted for multiple comparisons, $p < 0.05$). # Significantly different than zero (Bonferroni adjusted, $p < 0.05/2 = 0.025$).

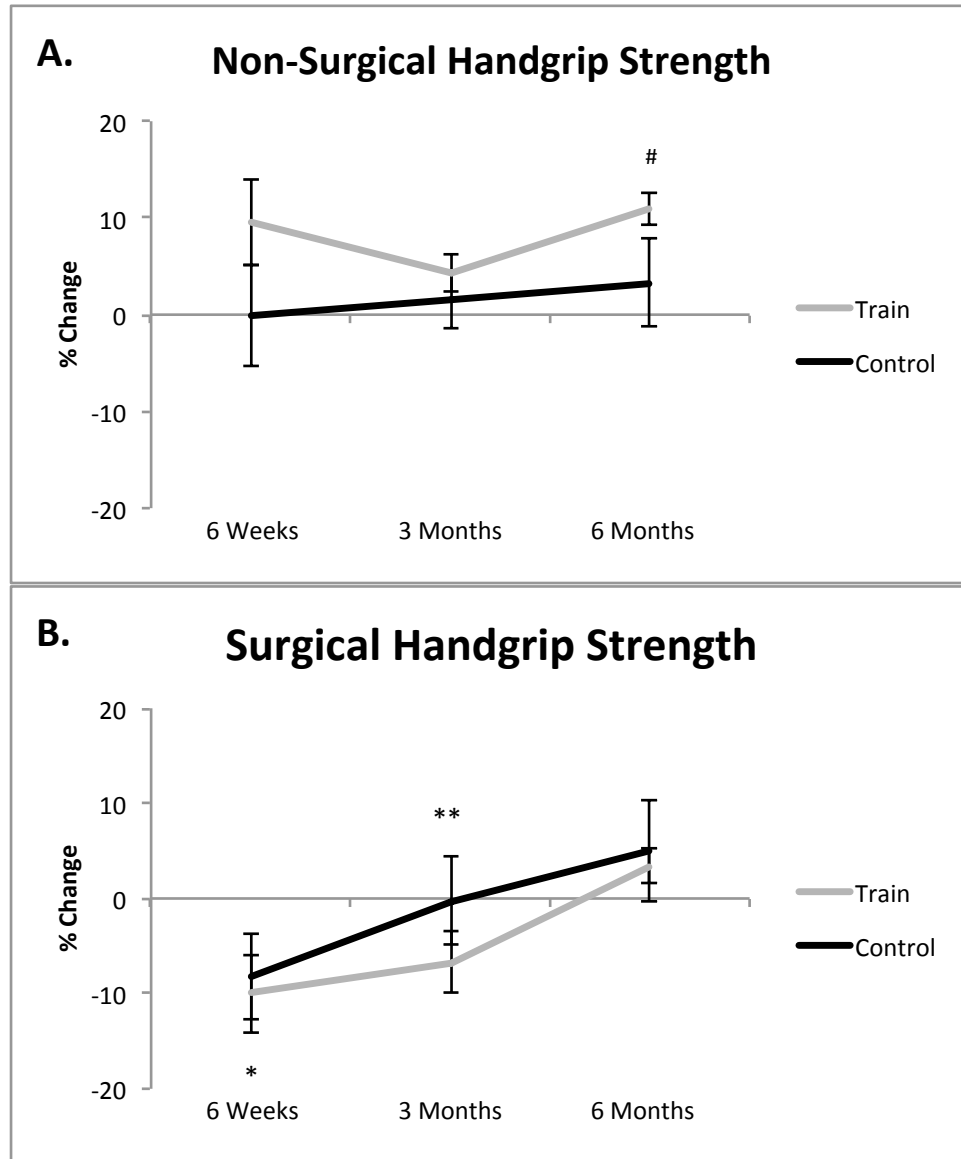


Figure 4.5 Percent change in handgrip strength. Values are means (\pm SE). Note: Both non-surgical and surgical arms were tested at all time points. A. Non-surgical arm percent change in strength. B. Surgical arm percent change in strength. * Significantly different than 3 months and 6 months pooled across groups (Bonferroni adjusted for multiple comparisons, $p < 0.05$). ** Significantly different than 6 months pooled across groups (Bonferroni adjusted for multiple comparisons, $p < 0.05$). # Significantly different than zero (Bonferroni adjusted, $p < 0.05/3 = 0.017$).

months (-22.9 ± 19.6) (Bonferroni adjusted, $p < 0.05/2 = 0.025$). Percent change in scaption strength for both arms is shown in Figure 4.4, and raw data are shown in Table 4.3.

For non-surgical handgrip strength, there were no significant differences in the overall repeated measures ANOVA; however, the one-sample t-tests showed that Train was significantly different than zero at 6 months ($11.0 \pm 5.2\%$) (Bonferroni adjusted, $p < 0.05/3 = 0.017$). There was a time main effect for surgical handgrip strength ($F(2,34) = 19.01$, $p < 0.001$) revealing that pooled across groups, 6 weeks was significantly different than 3 months and 6 months, and 3 months was significantly different than 6 months (Bonferroni adjusted for multiple comparisons, $p < 0.05$). There were no significant differences in the one-sample t-tests for surgical handgrip. Percent change in handgrip strength for both arms is shown in Figure 4.5, and raw data are shown in Table 4.3.

4.3.2 Muscle Thickness

The overall MANOVA showed a multivariate Group \times Time \times Arm interaction for the supraspinatus and anterior deltoid ($F(6,12) = 5.810$, $p = 0.005$). For the univariate analysis of the supraspinatus, there was a Group \times Time \times Arm interaction ($F(3,17) = 4.74$, $p = 0.005$). Post hoc analysis showed a significant difference between Train (2.23 ± 0.22 cm) and Control (1.85 ± 0.34 cm) in the surgical arm at 6 months (Bonferroni adjusted for multiple comparisons, $p < 0.05$). There were no significant differences in the non-surgical arm. For the univariate analysis of the anterior deltoid, there was a Time \times Arm interaction ($F(3,17) = 3.21$, $p = 0.031$) and a group main effect ($F(1,17) = 8.05$, $p = 0.011$) (Train had the greater muscle thickness pooled across time). Post hoc analysis showed that pooled across groups, there was a significant

difference between pre-surgery and 6 weeks in the surgical arm (unadjusted $p=0.012$, Bonferroni adjusted $p=0.071$). Muscle thickness data are in Table 4.4.

4.3.3 Active Range of Motion (AROM)

The overall MANOVA showed a time main effect for AROM ($F(6,12)=15.45$, $p<0.001$). For the univariate analysis of external rotation AROM, there was a time main effect ($F(3,17)=27.15$, $p<0.001$). Post hoc analysis showed that 6 weeks was significantly different than all other time points pooled across group, and 3 months and 6 months were significantly different pooled across groups (Bonferroni adjusted for multiple comparisons, $p<0.05$). For univariate analysis of scaption AROM, there was a time main effect ($F(3,17)=50.29$, $p<0.001$). Post hoc analysis showed that pre-surgery was significantly different than 6 weeks and 6 months pooled across groups, 6 weeks was significantly different than 3 months and 6 months pooled across groups, and 3 months was significantly different than 6 months pooled across groups (Bonferroni adjusted for multiple comparisons, $p<0.05$). Range of motion data are presented in Table 4.5.

4.3.4 Western Ontario Rotator Cuff Questionnaire (WORC)

For the WORC questionnaire, there was a significant time main effect ($F(3,17)=50.71$, $p<0.001$). Post hoc analysis revealed that pre-surgery was significantly different than 3 and 6 months pooled across groups, 6 weeks was significantly different than 3 and 6 months pooled across groups, and 3 months was significantly different than 6 months pooled across groups (Bonferroni adjusted for multiple comparisons, $p<0.05$). WORC data are presented in Table 4.6.

Table 4.4 Muscle thickness (cm) for supraspinatus and anterior deltoid. All values are means (\pm SD).

		Non-Surgical				Surgical			
		Pre-Surgery	6 Weeks	3 Months	6 Months	Pre-Surgery	6 Weeks	3 Months	6 Months
Supraspinatus	Train	2.17 (0.22)	2.26 (0.19)	2.27 (0.13)	2.22 (0.08)	2.09 (0.34)	2.00 (0.31)	2.14 (0.25)	2.23 (0.22) *
	Control	1.91 (0.57)	1.92 (0.54)	1.92 (0.60)	1.93 (0.45)	1.88 (0.55)	1.94 (0.51)	2.03 (0.46)	1.85 (0.34)
Anterior Deltoid	Train	1.41 (0.35) **	1.51 (0.26)	1.66 (0.36)	1.57 (0.21)	1.61 (0.41)	1.50 (0.36) ***	1.67 (0.47)	1.51 (0.23)
	Control	1.16 (0.42)	1.16 (0.35)	1.16 (0.37)	1.16 (0.36)	1.22 (0.40)	1.11 (0.44) ***	1.10 (0.37)	1.19 (0.35)

* Significant difference between groups (Adjusted for multiple comparisons, $p < 0.05$). ** Significant difference between groups at pre-surgery (unadjusted, $p = 0.049$). *** Significantly different than pre-surgery pooled across group (unadjusted, $p < 0.05$; when Bonferroni adjusted $p = 0.071$).

Table 4.5 Range of motion (degrees) for external rotation and scaption. All values are means (\pm SD).

		Pre-Surgery	6 Weeks	3 Months	6 Months
External Rotation	Train	51.2 (8.8)	19.3 (16.8) *	39.1 (11.1) **	55.3 (8.7)
	Control	47.6 (26.4)	22.9 (16.7) *	45.4 (22.9) **	54.9 (18.4)
Scaption	Train	144.8 (24.7) ***	63.4 (25.1)	127.6 (22.2) ***	147.7 (15.3) *
	Control	112.4 (42.3) ***	63.2 (48.6)	128.4 (30.5) ***	152.7 (16.0) *

Note AROM was taken on the surgical side only. * Significantly different than all other time points pooled across group (Bonferroni adjusted for multiple comparisons, $p<0.05$). ** Significantly different than 6 months pooled across group (Bonferroni adjusted for multiple comparisons, $p<0.05$). *** Significantly different than 6 weeks pooled across group (Bonferroni adjusted for multiple comparisons, $p<0.05$).

Table 4.6 Western Ontario Rotator Cuff Questionnaire (WORC) (% function). All values are means (\pm SD).

	Pre-Surgery	6 Weeks	3 Months	6 Months
Train	48.7 (10.3) *	37.2 (13.7) *	63.9 (16.3) **	75.5 (7.1)
Control	47.0 (19.1) *	46.5 (22.2) *	73.7 (18.2) **	91.0 (11.5)

Note: Scores are a percentage of overall function (i.e. higher percentage indicates better function). * Pre-surgery and 6 weeks are significantly different than 3 months and 6 months pooled across groups (Adjusted for multiple comparisons, $p<0.05$). ** 3 months significantly different than 6 months pooled across groups (Adjusted for multiple comparisons, $p<0.05$).

4.4 Discussion

The purpose of the study was to apply a clinically relevant shoulder strength training program (used in Experiment 2 of the Ph.D. thesis) to unilateral shoulder surgery participants, and determine if cross-education training could improve strength, muscle size, AROM, and self-reported function of the surgical limb. This study is novel as it is the first study to date that has applied cross-education to real shoulder surgery patients. The main finding was that there was no direct evidence that cross-education strength training altered the overall functional outcomes of the surgical limb; however, there was a cross-education effect for supraspinatus muscle thickness, and the strength training program effectively increased strength in the training limb.

Results showed that strength training of the non-surgical limb after shoulder surgery did not improve surgical limb strength, AROM, or the WORC questionnaire. The training group significantly increased percent change in strength in the non-surgical training arm; however, there was no transfer in strength to the surgical limb. The only other study that has applied cross-education to a real injury setting to date is Stromberg (1986; 1988) (reports from the same data set). Stromberg (1986; 1988) reported that cross-education strength training benefited the injured arm; however, this study had major limitations such as no reporting of raw data strength scores, which ultimately lead to inconclusive results. Since there is very little literature on the effects of cross-education in an injury setting, only speculation may explain why there were no significant strength effects to the surgical limb in this study. Perhaps the time from the injury to the surgery was the most crucial phase for altering the anatomy and function of the muscle. The shoulder injury occurred almost 2 years prior to the surgery on average for participants. Therefore, prior to the surgery, deleterious effects such as muscle atrophy and weakness may have already taken effect on the muscle. Unilateral training of the non-surgical limb would make

very little difference post-surgery if most of the negative effects had already taken place in the 2 years waiting for surgery. Patients who have surgery within less than one year after the onset of symptoms have greater rates for complete healing of the shoulder (Cho & Rhee, 2009). Possibly results would have been different if the training program was applied to the shoulder injury immediately after it occurred, or if cross-education was applied to a rehabilitation program with a more sudden injury that has immediate immobilization, such as after a fracture.

Another reason why significant strength effects to the surgical limb were not detected may be due to the variability in the injury itself. There are several factors that can affect the outcome of rotator cuff surgery, including the extent of the tear, location of the tear and the number of tendons involved (Millett et al., 2006). Participants with small tears will recover much faster than participants with very large tears (Cho & Rhee, 2009). The literature has also shown that patients who have undergone rotator cuff surgery do not progress in their rehabilitation at the same rate (Millett et al., 2006). In the present study, all sizes of rotator cuff tears were included due to the inability to gain standardized reporting of tear size from the surgeons. In addition, the study also included Bankart repair participants, which generally recover at a faster rate than rotator cuff patients (Rhee et al., 2007). All components of the injuries combined would have greatly increased the variability of the rehabilitation after surgery, making it more difficult to detect differences between groups with lower sample size. In addition, there is no record of compliance of the standard rehabilitation program for either group, and no record of the specific exercise programs given by the individual physical therapists. These factors would have also increased the variability in the measures.

Although cross-education had no effect on rehabilitation for strength, there was a significant difference between Train and Control for surgical muscle thickness at 6 months for

the supraspinatus (Train 2.23 ± 0.22 cm; Control 1.85 ± 0.34 cm) (Table 4.4). Muscle thickness of Train was significantly larger than Control at 6 months post-surgery, which theoretically may lead to improved strength and function for tasks targeting the supraspinatus. The supraspinatus is the muscle that is most commonly injured in rotator cuff tears (Cofield et al., 2001), making this finding very important. It is puzzling that the only indicator for cross-education to benefit rehabilitation in the surgical limb is the finding of a significant difference in muscle thickness at 6 months post-surgery. The increased supraspinatus muscle thickness in Train did not result in significantly greater shoulder strength at 6 months. With the higher coefficient of variation for the strength measures ($\sim 4.4\%$) as compared to muscle thickness ($\sim 3.7\%$), it remains possible that there was lack of sensitivity to detect the effects due to low sample size. The means for scaption strength at 6 months were very close between groups (Train $-22.5 \pm 26.9\%$; Control $-22.9 \pm 19.6\%$) (Figure 4.4). Scaption is the shoulder motion that mostly targets the supraspinatus, and the findings did not demonstrate any advantage for Train. Although the supraspinatus was significantly greater in muscle thickness for Train at 6 months post-surgery, it did not result in improved rehabilitation.

The anterior deltoid muscle thickness was not significantly different between groups post-surgery; however, there was a significant decrease in the surgical arm from pre-surgery to 6 weeks post-surgery pooled across groups (Table 4.4). The anterior deltoid was more affected by the immobilization than the supraspinatus after surgery and may have been more affected due to the incision site for the repair. The deltoid muscle is commonly split, and the tendon potentially removed and replaced in order to repair the muscle (Ghodadra et al., 2009). This could have potentially led to the significant decrease in thickness from pre-surgery to 6 weeks post-surgery. The supraspinatus may not have decreased as much from pre-surgery to post-surgery because of

the floor effect. The supraspinatus likely already had a large decline in muscle size, and fat infiltration (Melis et al., 2010) from the time of injury to the time of surgery. The mean time from the injury to surgery was 20.6 ± 22.4 months for Train and 19.6 ± 16 months for Control. Both groups had very similar wait times to surgery, with very large standard deviations, indicating that participants could have been waiting 3 to 5 years to repair their shoulders and this could have increased the variability in the measures across the whole sample.

The effects of the surgery on the strength of the surgical limb appeared to be very similar for both Train and Control. The shoulder motion that was most affected by the surgery was scaption. Both Train ($-46.3 \pm 33.9\%$), and Control ($-40.4 \pm 23.3\%$) significantly decreased scaption strength at 3 months. At 6 months, Train no longer had a significant decline in strength ($-22.5 \pm 26.9\%$); however, for Control the decline in strength remained significant ($-22.9 \pm 19.6\%$) (Figure 4.4). Although Train no longer had a significant decline at 6 months, the means between Train and Control were virtually the same, and the significant result for Control can be attributed to decreased variability. Ultimately, neither group fully recovered from the surgery for scaption strength at 6 months. It has been shown that any change greater than 11% using a handheld dynamometer to test shoulder strength is a clinically significant change (Magnusson et al., 1990). For all shoulder strength measures in both groups, there was a change in strength greater than 11% (range of 12.2% to 36.7%) from 3 to 6 months post-surgery. This indicates that both groups had clinically significant improvements in strength from 3 to 6 months post-surgery.

The strength training program significantly improved the percent change in strength for non-surgical external rotation and internal rotation. For external and internal rotation, Train was significantly stronger than Control pooled across time (Figure 4.2 and 4.3). The training group did not show a significant change in strength for scaption, and there were no significant

differences in scaption strength between groups (Figure 4.4). The changes in strength paralleled the findings in Study 2 of the thesis, whereby Train significantly increased strength by 10.9% for external rotation, 14.8% for internal rotation, and there were no significant increases in strength for scaption. The data suggests that the strength training program was effective for enhancing strength, and therefore the lack of observable cross-education effects cannot be attributed to an ineffective strength training intervention for the non-surgical limb.

For AROM, results showed there were no significant cross-education effects for external rotation or scaption. For the total sample of participants, AROM declined significantly from pre-surgery to 6 weeks post-surgery for external rotation (Train -31.9°; Control -24.7°) and scaption (Train -81.4°; Control -49.2°) (Table 4.5). From 3 to 6 months, external rotation and scaption AROM significantly improved, indicating enhanced recovery. The AROM means for Train and Control at 6 months were greater than at pre-surgery, showing evidence of full recovery after the surgery. The means for external rotation AROM are comparable to Choe and Rhee (2009) who found AROM was 53° post-surgery (current data: Train 55.3°; Control 54.9°, at 6 months post-surgery). Similarly, Petersen and Murphy (2011) found external rotation AROM to be 49° post surgery. For scaption AROM, the results at 3 months in the current sample (Train 127.6°; Control was 128.4°) were comparable to Moser et al. (2007) who found scaption to be 124.5° post-surgery.

For the WORC questionnaire, there were no significant differences between groups and there was no cross-education effect. Pre-surgery and 6 weeks post-surgery were significantly different than 3 months and 6 months pooled across groups, indicating that there was improved perceived function after the immobilization period. At 6 months post-surgery, percent function for Train was $75.5 \pm 7.1\%$, whereas for Control the percent function was $91 \pm 11\%$ (Table 4.6).

Importantly, the lack of significant effects for the WORC data are consistent with the lack of significant findings for strength. Where it is possible that the WORC did not accurately reflect the objective functional measures, this is unlikely because it is a valid and reliable tool for assessing rotator cuff repairs (Kirkley et al., 2003). However, it is not specific to Bankart repairs, which may be a limitation in using this tool to assess function in the patient population studied. Previous literature has shown the minimal clinically important difference for the WORC is 245 points (Kirkley et al., 2003), meaning that if a participant had a change of 200 points in score after treatment, there may not have been a true clinical change for the participant despite a numerical change in score. Results of the present study reported the percent function score; however, the change score in points for Train from pre-surgery to 6 months post-surgery was 563 points, and for Control was 924 points. This indicates that both groups likely had a true clinical change in function from pre-surgery to 6 months post-surgery.

One of the largest limitations to the present study was the sample size. The small sample size limited the study in a number of ways; including the decision to recruit Bankart repair surgery patients. Introducing a different type of shoulder surgery to the study increased the variability in a group of patients who already had a variety of rotator cuff tear sizes. In addition, the inability to classify the tears based on severity of the injury was important. The absence of this information limited the potential to co-vary out the severity of the injury in the data analysis. The small sample size was in part due to the difficulty in recruiting patients that only had shoulder pathology on one side. Participants needed to be able to complete the 6 month unilateral training program, and would be unable to successfully execute all exercises if they had an injury on the non-surgical shoulder. Although we screened for participants who only needed shoulder surgery on one side, we made the assumption that the non-surgical shoulder was

relatively normal. It is very likely that the non-surgical shoulder in some participants was not 100% functional. This would have affected the results when comparing the surgical arm back to the non-surgical arm as we did with the percent change in strength. Nonetheless, the non-surgical baseline scores served as the most appropriate reference value to quantify the changes in strength during recovery.

Another factor that may influence the results is limb dominance. Cross-education has been shown to transfer better in the dominant to non-dominant direction (Farthing et al., 2005). In the present study, there were 6 participants in Train and 9 participants in Control that had the surgery on their dominant arm. Theoretically, cross-education may have a greater effect if all surgeries were on the non-dominant side so the dominant side could complete the unilateral strength training program. Although cross-education may have better outcome with non-dominant surgeries, Binet et al. (2003) found that dominant arm shoulder surgeries recover better than non-dominant surgeries. There were no significant differences between the groups for limb dominance; however dominant and non-dominant side of the surgery is a factor should be taken into consideration.

This study was also limited in that we were unable to directly account for pain in our analysis. Pain has been shown to impact strength following shoulder injuries (Kirschenbaum et al., 1993; Klintberg et al., 2009), and pain significantly correlated with strength throughout the study. When using pain as a covariate in the analysis, the relationship between pain and strength was not consistent throughout each time point, which rendered the covariate analysis invalid. Despite the relationship between pain and strength of the surgical side at baseline, it could not be used as a valid covariate. Pain was significantly correlated with strength at baseline, therefore a percent change score from baseline of the non-surgical limb was used to help to account for the

potential confound of pain in the analysis. Pain was measured during the strength contractions for all tests on the surgical shoulder, and generally declined throughout the recovery (from pre-surgery to 6 months post-surgery). However, pain was still present during contractions at 6 months post-surgery for all strength tests (Table 4.2). This is consistent with other literature measuring pain during activity 6 months post shoulder surgery (Klintberg et al., 2009).

Lastly, the study was limited by not having the same rehabilitation staff carry out the surgery procedure and rehabilitation. Three different surgeons conducted the surgeries, which could have impacted the success of the surgery based on individual technique and experience. In addition, participants chose their own physiotherapist and received different rehabilitation instructions based on their individual needs. All participants followed the same standard rehabilitation programs from the orthopaedic surgeons; however, rehabilitation was likely influenced by the success of the surgery and the individual physiotherapy programs. Although this limitation could have prevented the detection of significant effects, it is more realistic to a real clinical setting where patients are exposed to different therapists and surgery interventions. Therefore a much larger sample size may be the best way to account for these potential confounders.

In conclusion, the study found no direct evidence that cross-education strength training altered the overall rehabilitation of the surgical limb; however, the training group had significantly greater supraspinatus muscle thickness than the control group at 6 months, and the strength training program effectively increased strength in the training limb. It is unclear why there was no significant cross-education effect to the surgical limb, but the limitations of this study, particularly low sample size, may have prevented the detection of effects. Although this study did not find significant results, it makes an important contribution to the field where there

is very little research conducted on clinical participants and data on long-term outcomes suggests that functional and strength deficits remain up to several years after surgery. More research is needed to determine if cross-education training can be used to benefit the recovery of the surgical limb after shoulder surgery in cases where there is prolonged pathology of the shoulder.

4.5 Relation of Experiment 3 to Thesis

The first objective of the thesis was to determine if cross-education could improve strength and functional performance of an immobilized limb using a shoulder sling model in both healthy and injured participants. The purpose of study three was to apply the clinically relevant shoulder strength training program (used in Experiment 2 of the Ph.D. thesis) to unilateral shoulder surgery participants, and determine if cross-education training can improve strength, muscle thickness, active range of motion (AROM), and self-reported function of the surgical limb. This study was necessary to complete the first objective of the thesis since it applied shoulder cross-education strength training to an actual injury setting.

Chapter 5: Experiment 4

Experiment 4 has been submitted to a peer-reviewed clinical rehabilitation journal and is currently being reviewed. It is presented in the submitted form with the exception of some minor changes necessary for the conversion to graduate thesis format.

5.1 Introduction

Cross-education is a neural adaptation defined as the increase in strength or functional performance of the untrained contralateral limb after unilateral training the opposite homologous limb (Farthing et al., 2005; Carroll et al., 2006). The increase in strength in the untrained limb is related to the gain in magnitude of the trained limb, and is on average 52% of the strength gain observed in the trained muscle (Carroll et al., 2006). Cross-education is thought to be primarily controlled by neural mechanisms (Carroll et al., 2006; Lagerquist et al., 2006; Farthing et al., 2007; Fimland et al., 2009; Farthing et al., 2011); however, the exact mechanisms are unknown.

A large gap in the literature remains in applying cross-education to clinical rehabilitation settings. The potential benefit of cross-education for rehabilitation from unilateral injuries (i.e. a fractured limb) is an obvious, medically relevant extension of the work; however, little research has been conducted in clinical application of cross-education (Stromberg, 1986; 1988) (reports from the same data set). Stromberg (1986; 1988) applied cross-education after wrist/forearm surgeries; however, limitations such as not including raw data, not accounting for baseline differences, and not reporting details of the training program have made it difficult to draw any conclusions from the results. Three studies have applied cross-education to unilateral immobilization in healthy (i.e. non-fractured) limbs (Farthing et al., 2009; Magnus et al., 2010; Farthing et al., 2011). Farthing et al. (2009) and Farthing et al. (2011) found cross-education strength training on the non-immobilized limb maintained strength in the immobilized healthy

limb after wearing a forearm cast for 3 weeks. Similarly, Magnus et al. (2010) found strength training the non-immobilized arm provided an increase in strength in the healthy immobilized arm after wearing an arm sling for 4 weeks. These studies suggest that cross-education can benefit a healthy immobilized limb; however, there are no randomized controlled clinical trials that have investigated these effects in real injuries. More research in this area may help improve the rehabilitation techniques clinicians use post-injury, and in turn may improve function for those with unilateral injuries such as distal radius fractures.

Distal radius fractures are one of the most common types of fracture (Larsen & Lauritsen, 1993), especially in older women (Handoll et al., 2006). The rehabilitation after a distal radius fracture is quite slow, and it can often be difficult for individuals to return to their normal level of functioning. Brogren et al. (2011) showed that 1-year post fracture grip strength was 88% of the non-fractured limb, with participants continuing to improve grip strength, pain and range of motion (ROM) up to 2-4 years post-fracture. Trumble et al. (1994) found that 2.4 years post-fracture grip strength was 69% of the non-fractured limb and ROM was 75% of the non-fractured limb. The assessment of function has been measured in studies using the Patient Rated Wrist Evaluation (PRWE). MacDermid et al. (2002) found that function (via the PRWE) in 120 distal radial fracture patients was not fully recovered 6 months post-injury. Similarly, Maciel et al. (2005) found that function (via the PRWE) was not recovered at 24 weeks post-distal radius fracture.

A Cochrane Review by Handoll et al. (2006) examined the effects of rehabilitation beginning both during and after immobilization in adults with distal radius fractures. There were various types of rehabilitation investigated, including at-home exercise programs, ultrasound, early referral and regular attendance to physical therapy, pulsed electromagnetic field therapy,

occupational therapy, passive mobilization, and programs with advice only for patients. Fifteen randomized controlled trials were included, whereby treatment was conservative, and involved plaster cast immobilization. The review found there was insufficient evidence to determine the best form of rehabilitation following distal radius fractures. New ways of improving rehabilitation to enhance recovery and to provide better functional outcome are important to investigate.

One way of improving strength and functional gains in the fractured hand may be to apply cross-education during recovery from unilateral distal radius fractures. Unilateral distal radius fractures represent an adequate clinical model to test the efficacy of cross-education due to the standard immobilization intervention of forearm casting for approximately 6-weeks. In our clinic, there is no rigorous therapeutic intervention prescribed for individuals beyond ROM and strengthening exercises for the fractured limb, and potential referral to physical therapy for more intensive treatment when deficits in function, ROM and strength cannot be addressed by home exercise alone. To our knowledge there are no rehabilitation protocols that incorporate a formal strength training program of the non-fractured side as part of the recovery for the fractured side following distal radius fractures (Handoll et al., 2006).

The purpose of this study was to apply cross-education to unilateral distal radius fractures in women 50 years of age and older and to evaluate the effects on grip strength, active ROM (AROM), and self-reported function. The hypothesis was that strength training of the non-fractured limb in addition to standard rehabilitation (an at-home program consisting of ROM and strengthening exercise of the fractured upper limb post cast removal) would provide better strength and functional outcome than standard rehabilitation alone after a unilateral distal radius fracture.

5.2 Methods

5.2.1 Participants

Women aged 50 years and older with a unilateral distal radius fracture were recruited from the fracture clinic at Royal University Hospital in Saskatoon, Saskatchewan, Canada under the direction of one orthopaedic surgeon. Patients referred to the clinic that met inclusion criteria, were invited to participate in the study prior to their first visit to the clinic. Exclusion criteria included any prior upper body injury or joint problem interfering with daily life, or any history of upper extremity neurological problems (i.e. stroke, multiple sclerosis, Parkinson's disease, vestibular disorders, reflex regional pain syndrome). Participants were also excluded if the fracture was greater than 2 weeks old at the time of the first visit to the clinic or if there were multiple fractures of the wrist and forearm. All participants completed the Mini-Cognitive Assessment Instrument for Dementia (Borson et al., 2000) to screen for cognitive impairment (Appendix F). Participants unable to remember any words in the word recall, or who scored an abnormal clock draw test and recalled only 1 or 2 words were not included in the study.

Thirty-nine women with an average age of 62.7 (± 9.7 years), height of 160.5 (± 6.9 cm) and weight of 67.7 (± 12.9 kg) were included in the final analysis for the study (see Figure 5.1 for Participant Enrolment Flow Diagram). A sample size calculation was completed using G Power 3.1 (Faul et al., 2009). Based on our previous immobilization cross-education studies involving forearm casting (Farthing et al., 2009; Farthing et al., 2011) we anticipated a 13% difference in affected limb strength between training and control. Since we have no previous data on cross-education effects on injured participants we used a much smaller effect size (ES) estimate based on a 5% difference between groups. Using α of 0.05 at 80% power, and an ES=0.2, the total

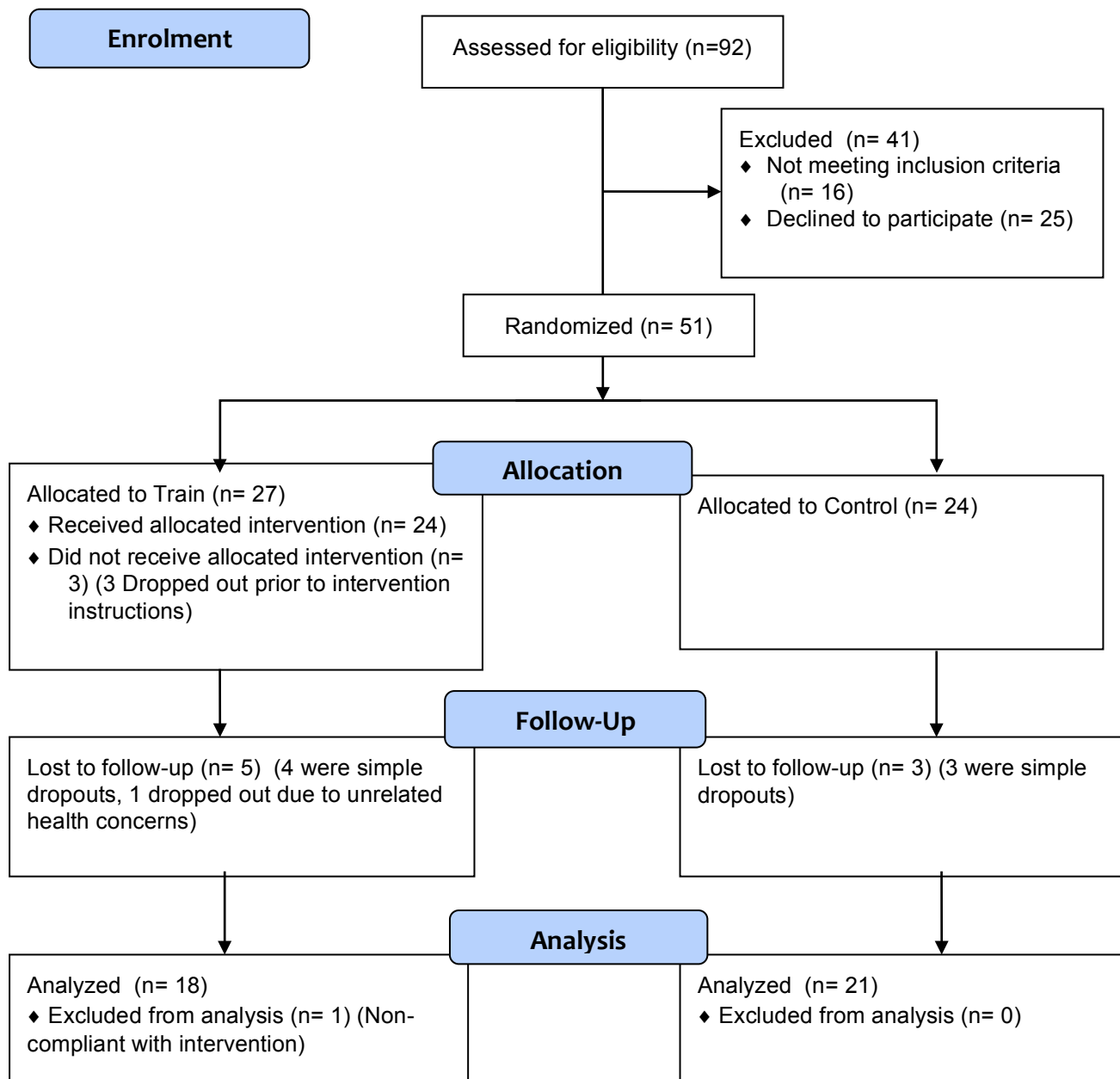


Figure 5.1 Participant enrolment flow diagram. Final n for Train =18. Final n for Control =21. Note: Simple dropouts are defined as those participants who dropped out of the study due to time constraints or due to loss of interest in the study.

required sample size was 36 (i.e. 18 per group). Prior to commencement of the study, all participants completed written informed consent approved by the Biomedical Ethics Review Board at the University of Saskatchewan with subsequent operational approval from the Saskatoon Health Region (see Appendix G for Certificate of Approval). Participants completed the Waterloo Handedness Questionnaire (WHQ) (Bryden, 1977) at the first clinic visit to determine handedness. The 10-item questionnaire is scored from -20 to +20, whereby negative scores indicate left-handedness, and positive scores indicate right-handedness. Participant descriptives per group are shown in Table 5.1.

5.2.2 Design

Participants were randomly assigned to one of two groups using a computer random number generator. Randomization was completed at the first visit to the clinic by a researcher who did not conduct any of the testing procedures. The orthopaedic surgeon, and all other testing staff (including those involved in strength assessment) were blinded to the randomization of groups to limit any bias, altered treatment, or encouragement during testing procedures. Group 1 received the standard clinical rehabilitation protocol after a distal radius fracture (Control), and Group 2 received the standard clinical rehabilitation protocol after a distal radius fracture, and strength trained their non-fractured limb throughout the duration of the study (Train). The standard clinical rehabilitation protocol included forearm casting, 6 visits to the fracture clinic at weeks 1, 3, 6, 9, 12, and 26 post-fracture, and the adoption of three paper-based (i.e. exercises were listed with instructions on a sheet of paper to participants) exercise protocols designed by a panel of physical therapists targeting the fractured side (in cast, six weeks post-fracture and nine weeks post-fracture) (See Appendix H for the exercise protocols given to

Table 5.1 Participant descriptive statistics for each group. Values are means (\pm SD).

	Age (years)	Height (cm)	Weight (kg)	Waterloo Handedness Score	Casting Period (days)	Dominant/ Non- Dominant Fracture	Number Fractures Repaired Surgically	Number Attended Physiotherapy
Train (n=18)	63.0 (8.2)	161.7 (6.9)	66.8 (13.6)	+13.0 (11.3)	42.2 (6.0)	Dom= 8 Non-Dom= 10	6	6
Control (n=21)	62.4 (10.9)	159.5 (6.9)	68.5 (12.5)	+16.0 (8.6)	38.9 (6.0)	Dom= 12 Non-Dom= 9	2	7

Dominant/Non-Dominant Fracture, Number of Surgeries and Number attended Physiotherapy are frequencies per group. There are no significant differences between groups for any participant characteristics.

participants). The orthopaedic surgeon coached each patient on each of the time-specific protocols at the appropriate time. Standard rehabilitation began with active ROM exercises for the neck, shoulder, elbow, fingers and thumb while in the cast. Once the cast was removed, exercises focused on improving active and passive ROM of the fractured wrist and hand (i.e. supination, pronation, flexion and extension). Stretching continued at 9-weeks post-fracture and strengthening exercises were integrated into the exercise regimen. Strengthening exercises such as wrist curls and gripping a soft ball/sponge/play dough were prescribed once per day. Participants were instructed to complete 10-12 repetitions. At 12-weeks post-fracture the patients are encouraged to continue with their exercises, and no formal limitations on their activity levels were imposed. The standard rehabilitation protocol encourages patients to continue these exercises throughout recovery; however, no training log or formalized regimen is implemented to track adherence. All exercises were to be completed at home, unsupervised on the patient's own time, with no prescribed exercises given to the non-fractured arm. Standard rehabilitation did not require patients to see a physiotherapist; however, some were referred by the orthopaedic surgeon or by their own family physician and attended physiotherapy on their own initiative (see Table 5.1).

Participants were tested at regular visits to the clinic (weeks 1, 3, 6, 9, 12 and 26); however, the present study only displays results from 4 time points: week 1 (1-2 weeks post-fracture), 9, 12, and 26. Week 1 is also referred to as the baseline testing session, although it was conducted 1-2 weeks post-fracture. Weeks 3 and 6 were not included in the analysis due to only the non-fractured side being measured at these time points (i.e. the fractured arm was unable to test strength and AROM at weeks 3 and 6).

5.2.3 Strength Training Intervention

The training group (Train) strength trained their non-fractured arm during the casting period, and continued to strength train their non-fractured arm throughout the follow-up (i.e. 26 weeks total). The strength training intervention was completed in addition to the standard clinical rehabilitation protocol described above. Strength training during the casting period was progressive in nature, beginning with 2 sets of 8 repetitions and increasing each training day by 1 set of 8 repetitions to a maximum of 5 sets of 8 repetitions of maximal voluntary effort handgrip contractions as tolerated. Five sets of 8 repetitions were continued throughout the 6 month duration of the training program.

Strength training of the non-fractured side began immediately after the first clinic visit. Handgrip training was performed using Cando Digi-Flex handgrip trainers (White Plains, NY) to train finger, hand and forearm strength (see Appendix I for picture of handgrip trainer). The resistance levels in the handgrip trainers ranged from extra light (0.7 to 2.3 kg) to extra heavy (4.1 to 14.1 kg). In the event that the extra heavy handgrip trainers were not strong enough, participants used coil ZoN Fitness Resistance Hand Grips (Northbrook, IL) to progress their training. Each maximal handgrip contraction was held for 3 seconds or as long as tolerated; and therefore was essentially isometric in nature. Participants were instructed to increase resistance with the coil resistance trainers by beginning with the hand at the bottom of the handles, and to move the hand up (closer to the coil) as the exercises became less difficult. Strength was assessed for each participant to determine which handgrip trainer to begin the training program. Participants tested different grip trainers that fit their level of strength until they felt comfortable beginning with a specific grip trainer. Progression in resistance was individually determined and monitored throughout the study by telephone calls and at subsequent visits. Participants

completed the exercises 3 times per week, and recorded adherence in a training log monitored by the researchers (See Appendix J for training log). Participants had to complete at least one training session/week (on average) to be considered trained and included in the final data analysis. The strength training intervention was unsupervised and conducted individually at home. Training participants were contacted via telephone bi-weekly to encourage adherence and to monitor training. To ensure there was no effect of the phone calls on rehabilitation, Control was also called via telephone bi-weekly and was asked how their wrist was feeling, and if there had been any changes in their wrist since the last time they were contacted.

5.2.4 Strength

Isometric grip strength was assessed using a calibrated Baseline Hydraulic Hand Dynamometer (White Plains, NY). Testing was conducted with participants seated, the shoulder completely adducted, elbow flexed at 90°, and the wrist in neutral position (palm facing medially). A standard distance for the handgrip position (i.e. distance of the fingers from the gripper) was used for all participants. The peak value obtained from three maximal voluntary efforts was used for comparison. The contractions were 3 seconds in duration with each contraction separated by 1-minute rest. The non-fractured extremity was always tested first. At week 1, grip strength was assessed on the non-fractured side only. Week 9 (i.e. 3 weeks after cast removal) was the first time point that participants were able to complete a maximal contraction on the fractured side. Both sides were tested for strength at weeks 9, 12 and 26. Participants were instructed to squeeze the dynamometer as hard as they could for the three second duration of the contraction and were given verbal encouragement at each trial. To minimize the learning effect, all participants were familiarized with the dynamometer prior to the

contractions.

5.2.5 Active Range of Motion (AROM)

AROM was assessed manually using a Jamar goniometer for wrist flexion, extension, supination, and pronation using a standard protocol. Participant's actively moved their wrist in the desired motion until the end ROM or until the point of discomfort. Wrist flexion and extension scores were added together to give a combined flexion/extension range. Supination and pronation were also added together for a combined supination/pronation range. All measures were conducted with the participant seated, shoulder fully adducted, and the elbow bent 90°. AROM was measured on the fractured limb only at weeks 9, 12, and 26.

5.2.6 Patient Rated Wrist Evaluation (PRWE)

The PRWE (MacDermid et al., 1998) is a 15-item questionnaire designed to assess wrist pain and function with activities of daily living. The PRWE is a valid and reliable tool to assess outcome in wrist fractures (Changulani et al., 2008). Respondent's self-reported levels of wrist pain and function using a scale ranging from 0 to 10 (0=no pain/no difficulty; 10=worst pain/unable to do activity). A total score was calculated by adding the responses for each question (best score=0; worst score=150) (See Appendix K for PRWE). Results for the PRWE are shown for weeks 1, 9, 12, and 26. Week 1 was answered as a retrospective pre-fracture score and was taken at the first visit to the clinic. Weeks 9, 12, and 26 were completed for the corresponding time point post-fracture.

5.2.7 Data Analysis

All data were analyzed using SPSS 20.0 and was checked for normality using skewness and kurtosis tests. Little's MCAR (Missing Completely at Random) test was used to determine that strength ($\chi^2(32)=39.89, p=0.159$), AROM ($\chi^2(12)=11.75, p=0.466$), and PRWE ($\chi^2(20)=22.87, p=0.295$) were missing completely at random. There was a total of 21/312 missing data points for strength, 24/234 for AROM, and 28/156 for the PRWE. Group series means were used to replace all missing data (Tabachnick & Fidell, 2013). Strength was analyzed using a Group (Train, Control) \times Time (Week 1, 9, 12 and 26) \times Arm (Fractured, Non-fractured) repeated measures ANOVA (analysis of variance). Week 1 (i.e. baseline) strength values for the non-fractured arm were used as week 1 strength values for the fractured arm. The non-fractured arm baseline measurement was also assumed as the fractured arm baseline measurement since it was impossible to get a strength measure on the fractured arm at week 1. AROM (fractured arm only) was analyzed using a Group (Train, Control) \times Time (Week 9, 12 and 26) repeated measures ANOVA. The PRWE was analyzed using a Group (Train, Control) \times Time (Week 1, 9, 12 and 26) repeated measures ANOVA. Week 1 for the PRWE was a retrospective pre-fracture score. If significant main effects or interactions were detected, simple main effects analysis continued using one-way ANOVA and Bonferroni adjustments. Bonferroni adjustments were made using SPSS programming where possible (identified by stating Bonferroni adjustments were made for multiple comparisons) or were adjusted for manually by dividing by the number of tests (i.e. $p < 0.05/3 = 0.017$). Significance was accepted at $p < 0.05$.

5.3 Results

5.3.1 Strength

There was one non-adherent participant in Train that did not complete the minimum requirement of strength training sessions and therefore, was not included in the data analysis. We used completer-only analysis and not intention-to-treat analysis (ITT) to determine if the trial would work in a group of adhering participants. This was the first clinical trial that attempted to apply cross-education in a wrist fracture setting and future trials may use ITT to determine the outcome in both adhering and non-adhering participants once the preliminary trial has been conducted. There were no significant differences between groups for strength at Week 1 for the non-fractured arm. There was a significant Group \times Time interaction ($F(3,37)=4.01$, $p=0.009$, Partial $\eta^2=0.098$), and a significant Time \times Arm interaction ($F(3,37)=108.38$, $p<0.001$, Partial $\eta^2=0.745$). Despite the fact that the 3-way interaction was not significant, we justified analyzing group \times time interactions for each arm separately given that the primary purpose of the study was to directly compare the outcome of the fractured arm. Post hoc analysis revealed that the non-fractured arm of Train significantly increased strength from Week 1 ($28.1\pm6.0\text{kg}$) to Weeks 9 ($30.8\pm6.9\text{kg}$), 12 ($30.7\pm6.5\text{kg}$), and 26 ($31.0\pm6.9\text{kg}$), (Bonferroni adjusted for multiple comparisons, $p<0.05$) (Figure 5.2). The non-fractured arm of Control significantly decreased strength from Week 9 ($26.9\pm4.4\text{kg}$) to Week 12 ($24.9\pm4.4\text{kg}$), (Bonferroni adjusted for multiple comparisons, $p<0.05$). There was a significant difference between groups at 9, 12 and 26 weeks for non-fractured arm strength ($p<0.05$), and when Bonferroni adjusted; week 12 remained significantly different ($p<0.05/3=p<0.017$).

For fractured arm strength, Week 1 was significantly different than all other time points for both Train and Control (Bonferroni adjusted for multiple comparisons, $p<0.05$) (Figure 5.3).

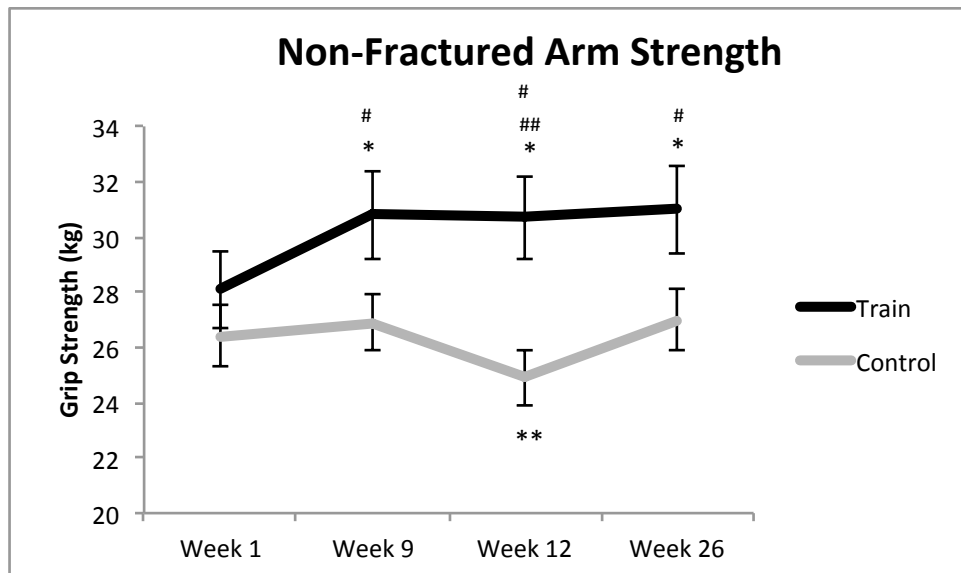


Figure 5.2 Non-fractured limb handgrip strength. Values are means (\pm SE). There was a significant Group \times Time interaction, and a significant Time \times Arm interaction for strength ($p < 0.05$). * Significantly different than Week 1, ** Significantly different than Week 9 (Adjusted for multiple comparisons, $p < 0.05$). # Significant difference between groups (unadjusted), ## Significant difference between groups (Bonferroni adjusted, $p < 0.05/3 = 0.017$).

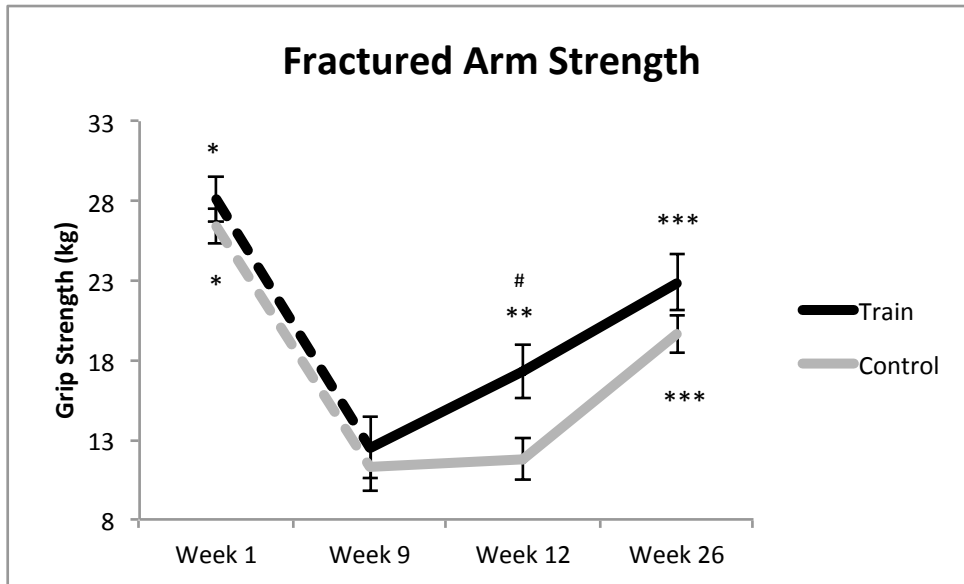


Figure 5.3 Fractured limb handgrip strength. Values are means (\pm SE). There was a significant Group \times Time interaction, and a significant Time \times Arm interaction for strength ($p < 0.05$). Note: Dotted line is Week 1 non-fractured limb strength. * Significantly different than all other time points, ** Significantly different than Week 9, *** Significantly different than Week 9 and 12 (Adjusted for multiple comparisons, $p < 0.05$). # Significant difference between groups (Bonferroni adjusted $p < 0.05/3 = 0.017$).

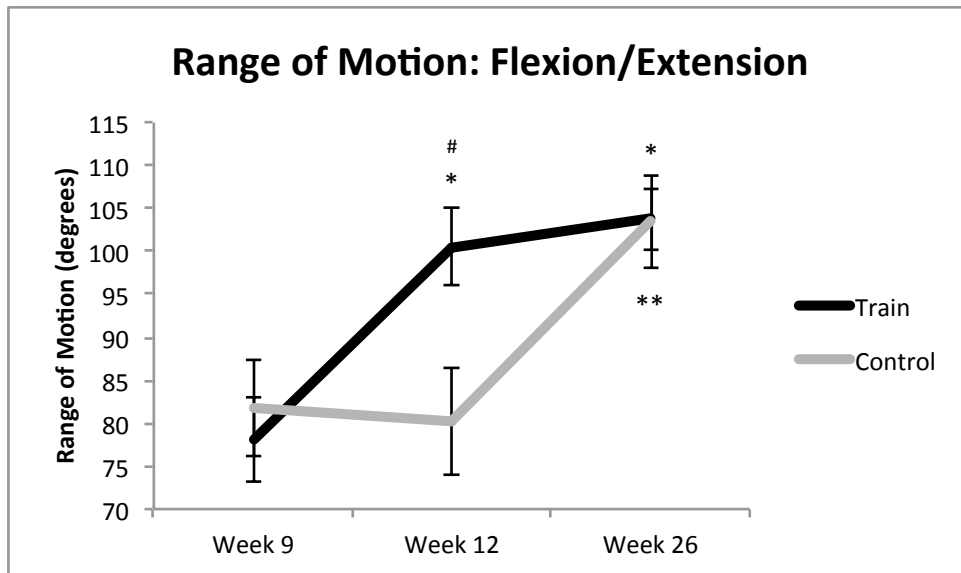


Figure 5.4 Flexion/extension AROM for fractured hand only. Values are means (\pm SE).
 * Significantly different than Week 9, ** Significantly different than Week 9 and 12
 (Adjusted for multiple comparisons, $p < 0.05$). # Significant difference between groups
 (Bonferroni adjusted, $p < 0.05/3 = 0.017$).

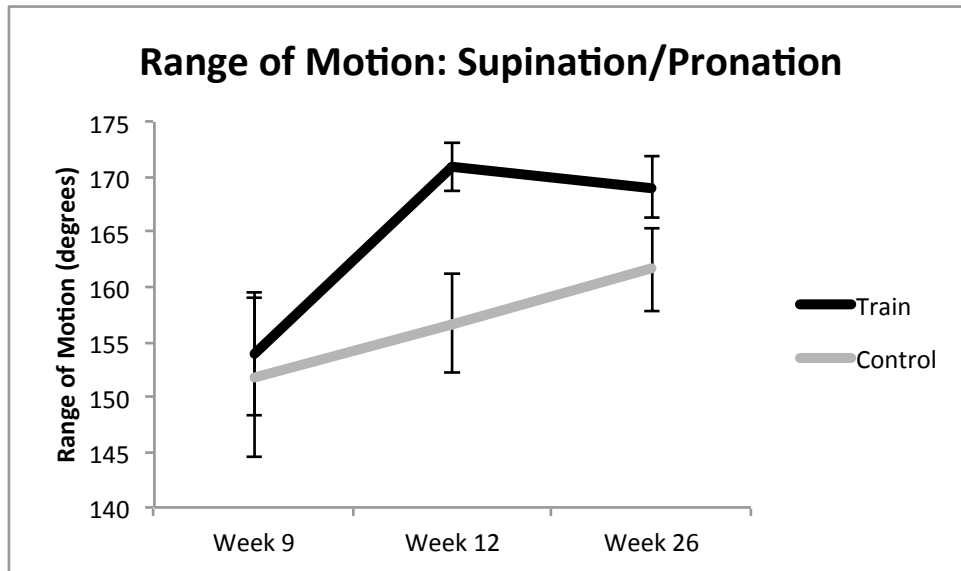


Figure 5.5 Supination/pronation AROM for fractured hand only. Values are means (\pm SE). No significant differences.

Table 5.2 Patient Rated Wrist Evaluation (PRWE). All values are means (\pm SD)

	Week 1	Week 9	Week 12	Week 26
Train	3.1 (4.2)	54.2 (39.0)	36.4 (37.2)	23.6 (25.6)
Control	6.4 (6.0)	65.2 (28.9)	46.2 (35.3)	19.4 (16.5)

There are no significant differences. Note: A high score is more symptomatic. Week 1 is retrospective pre-fracture score and Weeks 9, 12, & 26 are post-fracture scores for corresponding time points.

For the fractured arm of Train, Week 9 ($12.5 \pm 8.2\text{kg}$) was significantly different than Week 12 ($17.3 \pm 7.4\text{kg}$); and Weeks 9 and 12 were significantly different than Week 26 ($23.0 \pm 7.6\text{kg}$) (Bonferroni adjusted for multiple comparisons, $p < 0.05$). For the fractured arm of Control, Weeks 9 ($11.3 \pm 6.9\text{kg}$) and 12 ($11.8 \pm 5.8\text{kg}$) were significantly different than Week 26 ($19.6 \pm 5.5\text{kg}$) (Bonferroni adjusted for multiple comparisons, $p < 0.05$). There was a significant difference between Train and Control for fractured arm strength at 12 weeks post fracture ($17.3 \pm 7.4\text{kg}$ and $11.8 \pm 5.8\text{kg}$, respectively) (Bonferroni adjusted, $p < 0.05/3 = 0.017$).

5.3.2 Active Range of Motion (AROM)

For AROM, there was a significant Group \times Time interaction for flexion/extension ($F(2,37)=8.20$, $p=0.001$, Partial $\eta^2=0.181$), and a significant time main effect for flexion/extension ($F(2,37)=30.09$, $p<0.001$, Partial $\eta^2=0.449$), and supination/pronation ($F(2,37)=8.13$, $p=0.001$ Partial $\eta^2=0.180$). Post hoc analyses revealed that for flexion/extension in Train, Week 9 ($78.1 \pm 20.7^\circ$) was significantly different than Weeks 12 ($100.5 \pm 19.2^\circ$) and 26 ($104.4 \pm 15.5^\circ$) (Figure 5.4) (Bonferroni adjusted for multiple comparisons, $p < 0.05$). For Control, Weeks 9 ($81.7 \pm 25.7^\circ$) and 12 ($80.2 \pm 28.7^\circ$) were significantly different than Week 26 ($106.0 \pm 26.5^\circ$) (Bonferroni adjusted for multiple comparisons, $p < 0.05$). There was a significant difference between Train ($100.5 \pm 19.2^\circ$) and Control ($80.2 \pm 28.7^\circ$) at 12 weeks post-fracture for flexion/extension AROM (Bonferroni adjusted, $p < 0.05/3 = 0.017$). There were no significant group differences for supination/pronation AROM (Figure 5.5).

5.3.3 Patient-Rated Wrist Evaluation (PRWE)

There were no significant differences between groups at Week 1 for the PRWE. There was a time main effect pooled across group ($F(3,37)=48.93, p<0.001$, Partial $\eta^2=0.569$); however, there were no significant differences found (Table 5.2).

5.4 Discussion

The main finding of this study was that strength training the non-fractured arm after a distal radius fracture improved strength and AROM at 12 weeks post-fracture in the fractured arm. These results demonstrate that cross-education strength training is beneficial to older women in early recovery following a distal radial fracture. To our knowledge this is the first well-controlled, randomized trial to demonstrate the efficacy of the cross-education effect in a clinical setting. These results have important implications for changing current rehabilitation protocols in the early recovery stages post-distal radius fracture and may be generalized to other unilateral injuries, following further investigation.

Recent research has focused on applying cross-education training protocols to unilateral limb immobilization (Farthing et al., 2009; Magnus et al., 2010; Farthing et al., 2011). Farthing et al. (2009), Farthing et al. (2011) and Magnus et al. (2010) showed that a healthy immobilized limb is able to maintain, or even improve strength following cross-education strength training of the non-immobilized limb. Many studies indicate that cross-education may benefit recovery following unilateral injury; however, only one other study has attempted to apply cross-education to a clinical setting (Stromberg, 1986; 1988) (reports from the same data set). Stromberg (1986; 1988) applied cross-education to a variety of hand/forearm injuries and

reported that cross-education training improved rehabilitation; however, limitations such as not accounting for baseline differences, not reporting the training program, and not reporting raw data make it difficult to draw any valid conclusions from the results.

The results of the present study showed that Train had a quicker recovery in both strength and AROM on the fractured limb compared to Control. Control had a 4.4% increase in strength from week 9 to 12, whereas Train had a 38.4% increase in strength from 9 to 12 weeks (Figure 5.3). For handgrip strength the minimal clinically significant difference (MCID), the minimum change in a score that indicates a meaningful difference for the patient (Smith et al., 2012) has been identified as a change of 6 kg (Nitschke et al. 1999). In the present study, a change of greater than 6 kg was found for both Train and Control at 26 weeks post-fracture. Results for flexion/extension AROM showed that Control had a slight decline in range of -1.8% from 9 to 12 weeks post-fracture, and Train showed an increase in range of 28.7% (Figure 5.4). This indicates that Control had no improvement in flexion/extension AROM from 9 to 12 weeks, whereas Train was almost fully recovered by 12 weeks post-fracture. The MCID for ROM is 13.5 degrees (Witthaut et al., 2011). Train showed a clinically important change for flexion/extension AROM from 9 to 12 weeks (change for Train 22.4°; change for Control 1.5°), whereas Control did not show an increase in AROM until 26 weeks post-fracture. Although supination/pronation AROM was not significantly different between groups, it had similar trends whereby Control increased range 3.2% from 9 to 12 weeks post-fracture, and Train increased 11.0% (Figure 5.5). Train showed a clinically important change from 9 to 12 weeks post-fracture for supination/pronation AROM (change for Train 17°; change for Control 4.9°); whereas Control did not show a clinical change even at 26 weeks post-fracture (change of 11°).

The decline in strength post wrist fracture is comparable with other literature investigating grip strength after wrist fractures (Földhazy et al., 2007). Földhazy et al. (2007) found that 12 weeks post distal radius fracture grip strength was approximately 65% of the non-fractured limb, whereas our results showed grip strength was 62% of the non-fractured limb for Train, and 45% for Control. At 26 weeks post-fracture, Földhazy showed strength was 76% of the non-fractured limb, and Train and Control were 82%, and 74%, respectively. It is difficult to directly compare the two studies considering Földhazy's study only included participants with non-surgical fractures and the present study included participants with both surgical and non-surgical fractures. In the present study, surgical participants had lower strength scores on average compared to non-surgical participants. If the present study excluded surgical participants, it may have improved the overall mean strength scores. This may suggest that when compared to other wrist fracture literature, strength training of the non-fractured limb improves strength of the fractured limb.

Significant differences in strength between Train and Control were evident at 12-weeks post-fracture; roughly 6 weeks after the immobilization period ended. Why significant differences were shown at 12 weeks, and not 9 weeks is unknown. It is possible that at 9 weeks post-fracture participants were still very sore, and potentially so sore that the pain during a handgrip contraction prevented comfortable and maximal strength testing. At 12 weeks post-fracture, the participants may have been much more comfortable completing a maximal handgrip test, which may have accounted for the significant difference at 12 weeks.

Cross-education literature from non-injury settings have shown the effect occurs in training programs varying from 3-8 weeks in duration (Kannus et al., 1992; Farthing et al., 2003; Farthing et al., 2005; Munn et al., 2005); therefore it may be expected that significant effects

would be shown prior to 12-weeks post fracture (i.e. at 9 weeks). Perhaps if participants were tested weekly for strength between week 9 and 12, significant differences may have been shown prior to 12 weeks post-fracture. The significant effect at 12 weeks may be due to the time course of the injury itself (i.e. the injury delayed the response to cross-education), which could have altered the neurological transfer in strength that would normally be shown in cross-education training without an injury. More research is needed to further investigate the time course and mechanisms behind these effects in a clinical setting.

Importantly, the cross-education home-based strength training program effectively increased strength in the non-fractured hand of Train from week 1, to weeks 9, 12, and 26. Train showed an average increase in strength of 9.6% (average from weeks 9, 12 and 26). This increase in strength is comparable to Farthing et al. (2011) who showed a 10.7% increase in handgrip strength in the trained limb using a supervised lab-based training program. The present study is also novel because of the unsupervised, at-home strength training program. Cross-education strength training studies have typically been completed in supervised controlled lab environments. Therefore, a 9.6% increase in strength from an at-home grip strength program demonstrates this type of training is quite feasible in a clinical environment where supervised training is more difficult or impossible.

Cross-education is known to produce contralateral limb strength adaptations following unilateral training; however, there is no apparent evidence to suggest that cross-education strength training can produce increases in AROM of an opposite limb. The present study showed that Train had significantly improved wrist flexion/extension AROM at 12-weeks post fracture compared to Control, and trends suggested that Train also had improved supination/pronation compared to Control, although not significant. Evidence is limited in

examining the effects of cross-education on ROM. Nelson et al. (2012) investigated the effect of unilateral stretching on strength in the opposite limb; however, to our knowledge there are no studies that have investigated the effect of unilateral strength training on ROM in the opposite limb. The improved AROM of Train may be due to the training group adhering to the exercises on the fractured limb better than Control. Since participants in the training program were strength training their non-fractured arm 3 times/week during the 6-month duration of the study, this may have served as a reminder to continue with the exercises from the orthopaedic surgeon. More research is needed to determine if cross-education strength training can produce increased AROM in the opposite limb.

There were no significant differences between groups for supination/pronation AROM. This is likely due to the quick recovery of supination/pronation for both groups, and a ceiling effect for the total ROM. Train already had a range of 153.9° at 9-weeks post-fracture, and improved to 169.4° at 26-weeks post fracture. Similarly, Control had a range of 151.8° at 9-weeks and 162.8° at 26-weeks post-fracture.

There were no significant differences between Train and Control for the PRWE (Table 5.2). Significant differences were likely not detected due to the high variability of the measure. Based on current data, there is no evidence to suggest the cross-education intervention had a significant impact on self-reported pain and function during activities of daily living of the fractured limb, despite evidence for improved strength. The PRWE is the most commonly used instrument for evaluating functional outcome in patients with distal radius fractures (Changulani et al., 2008); however, it may not be sensitive enough to detect small changes between groups. A more direct measure of function may be necessary to accurately assess the effects on recovery. Although significant differences were not detected between the groups, both groups showed a

clinical improvement in self-reported function by 26 weeks. The MCID for the PRWE is a change of 24 points (16%) (Schmitt & Di Fabio, 2004). Train had a change of 30.6 points from 9 to 26 weeks and Control had a change of 45.8 points from 9 to 26 weeks.

One limitation of the present study is that we cannot be certain that Train completed the exercises as prescribed. The training program was taught to the intervention group at the initial visit to the clinic, and was completed unsupervised at the participants' home. This self-monitored at-home program was chosen as it could be implemented in such a manner that would decrease participant travel burden and decrease clinical visits. Despite the unsupervised nature of the program and the uncertainty regarding adherence, it was effective for increasing strength. Arguably the strength increase for Train was partly due to using their non-fractured arm more than normal for daily activities. However, Control would have also used their non-fractured arm the same amount as Train, and Control showed a significant decrease in strength from week 9 to 12. This is important because it points towards the possibility of a global strength decline in both arms following a unilateral distal radius fracture when attempting to implement the current clinical practice. This may suggest that patients may not be adhering to the standard rehabilitation program.

Another potential limitation is that we did not account for the effect of physical therapy or surgery in the analysis. Conveniently, the number of participants who attended physical therapy was very similar between groups (Train 6; Control 7); therefore this even distribution should not have affected the results if the physical therapy treatments received in each group were similar. For the number of surgeries, there were 6 participants in Train, and 2 in Control who had surgery. Not all surgeries were conducted prior to entering the study (i.e. some surgeries occurred after wearing the cast for a number of weeks); therefore, surgical participants

were included in the study to limit dropouts if surgery occurred after randomization and to increase the sample size. Surgical participants had lower strength scores on average compared to non-surgical participants in the fractured arm at 9 (8.3% weaker), 12 (18.1% weaker) and 26 (15.1% weaker) weeks. Train had four more surgical participants than Control, therefore this may have served to reduce, rather than enhance, the overall cross-education effect. Results may have in fact been stronger if surgical participants were excluded in the analysis. An additional limitation is that we did not do sub-group analyses due to the small sample size. Further analysis could have consisted of dividing by age, and surgical/non-surgical fractures. Future studies may investigate these factors, and may also look at a longer term of follow-up to determine the effects on overall function.

In conclusion, the present study found that strength training the non-fractured limb was associated with significantly improved strength and AROM in the fractured limb via cross-education in the early stages of rehabilitation. This study marks a crucial advancement in the field, as it is the first randomized controlled trial to demonstrate that training of a non-injured limb can benefit an injured limb. These findings may be applied to other unilateral injuries, and may have implications for altering the current clinical rehabilitation protocols following wrist fractures. Future research may investigate cross-education effects in other types of injuries, the effects over longer follow-up, and the mechanisms behind the effect.

5.5 Relation of Experiment 4 to Thesis

The second objective of the thesis was to determine if cross-education could improve strength and functional performance of wrist fracture rehabilitation after unilateral training of the non-fractured limb. The purpose of study four was to apply cross-education to unilateral distal

radius fractures and to evaluate the effects on grip strength, active ROM, and self-reported function. Since previous work had been completed in forearm immobilization models in healthy participants (Farthing et al. 2009; 2011), this was the only study that was needed to meet the second objective of the thesis.

Chapter 6: General Discussion and Conclusion

6.1 Summary of Major Findings

The first objective of the thesis was to determine if cross-education would improve strength and functional outcome of an immobilized limb using a shoulder sling model in both healthy and injured participants. Study 1 was the first to apply cross-education during 4 weeks of unilateral limb immobilization in healthy participants using a shoulder sling and swathe model. The cross-education effect increased elbow extension strength and maintained muscle size in the immobilized arm of the training group. These results are consistent with three other studies reporting a beneficial effect of cross-education to a healthy immobilized limb using both casting (Farthing et al., 2009; 2011) and arm sling models (Pearce et al., 2012). Study 2 applied cross-education using a clinically relevant at-home resistance tubing shoulder strength training program (that is commonly used in rehabilitation settings) to healthy participants. At-home shoulder training program resulted in cross-education effects for shoulder external and internal rotation and was effective for enhancing supraspinatus and anterior deltoid muscle size in the trained limb. Importantly, this was the first study to demonstrate the efficacy of an at-home resistance tubing strength training program to produce increases in strength in both limbs, and has implications for rehabilitation after unilateral shoulder injuries.

Study 3 extended the findings of Study 1, and applied cross-education to shoulder surgery recovery using the clinically relevant strength training program (used in Study 2) and measured strength, muscle size, AROM, and the WORC questionnaire. The intervention had a significant increase in supraspinatus muscle thickness for the training group at 6 months post-surgery; however, there were no cross-education effects for strength, AROM, or the WORC. The intervention did not improve the overall recovery of the surgical limb after shoulder surgery,

although there was a significant cross-education effect for muscle thickness. Study 1 and 2 provide evidence for the potential use of cross-education in clinical settings; however, when cross-education was applied to a clinical post-shoulder surgery setting, functional improvements in strength were not detected.

The second objective of the thesis was to determine if cross-education could improve strength and functional outcome of wrist fracture rehabilitation after unilateral training the non-fractured limb. As a natural extension of previous work demonstrating beneficial effects of cross-education using healthy forearm casting models (Farthing et al., 2009; 2011), Study 4 applied cross-education during rehabilitation from wrist fractures and measured strength, AROM, and the PRWE. The cross-education intervention improved handgrip strength and AROM in the fractured limb 12 weeks post-fracture; however, this was not sustained at 26 weeks post-surgery. Study 4 is the first to demonstrate that cross-education strength training is feasible and effective in early rehabilitation post wrist fracture, but further study is needed to justify the long-term outcome.

6.2 Application of Cross-Education to Healthy Immobilization Models

There are now four studies that have used immobilization models to apply cross-education in healthy (i.e. non-injured) participants: Farthing et al., (2009; 2011), Pearce et al. (2012), and Study 1 in the thesis. Study 1 was the first immobilization model to apply cross-education to a type of immobilization other than forearm casting. The model of shoulder slinging used in Study 1 allowed for muscle activation to be measured due to the removable sling. Shoulder slinging also was a good model to use in the application of cross-education since rotator cuff pathology is one of the most common types of upper extremity injuries (Herberts et

al., 1984), and typically results in immobilization in a sling. Although the slinging model allowed for more convenient access to the muscle, one limitation was that participants were able to remove their sling at any time during the day, even though they were instructed to only remove it for sleeping, bathing and driving. The amount of time the sling was removed was tracked using daily immobilization logs. Participants were instructed to wear the sling a minimum of 12 to 14 hours per day, but it could not be guaranteed that the amount of time the sling was worn was an accurate representation of the amount of time reported by participants, or whether or not the hours were accumulated continuously or by separate intervals. Despite the limitations of the slinging model, Study 1 provided evidence of decreased muscle size and strength with the immobilization intervention (non-training group) and the training intervention generated significant cross-education effects. The slinging model was then replicated by Pearce et al. (2012) who also found unilateral strength training benefited the immobilized limb.

Evidence from all four studies using the cross-education and immobilization model suggests there is a profound maintenance effect for the opposite immobilized limb during short-term immobilization of 3-4 weeks. Furthermore, the studies point towards great potential for cross-education to be used in real injury immobilization settings. Although model immobilization studies provide this evidence, the effect of cross-education in real injury settings remains uncertain for shoulder rehabilitation, but shows more promise for post-wrist fracture rehabilitation.

6.3 Application of Cross-Education to Injuries

Including the thesis studies, there are now three studies that have applied cross-education to real injuries: Stromberg, 1986; 1988 (reports from the same data set), Study 3, and Study 4.

Stromberg (1986; 1988) was the first study to apply cross-education to an injury setting, using participants who had elective upper extremity surgery (i.e. carpal tunnel surgery or collateral ligament repair) resulting in splinting for three weeks. The study randomized 20 participants into 2 groups, and measured strength and ROM. Stromberg concluded that strength and ROM were markedly improved in the strength training group. The means for percent change in strength and ROM were better in the training group compared to the control group; however, the training group started with a higher mean post-surgery, and both groups recovered at the same rate. Baseline differences were also evident in Stromberg's study but they were not accounted for. There is unfortunately no definitive evidence that can be drawn from the work of Stromberg despite the attempt to incorporate a novel cross-education intervention in a post-surgery setting.

The shoulder surgery results in Study 3 were similar to those from Stromberg (1986; 1988) for strength recovery, where strength in the training group was better overall, and both groups generally improved at the same rate. The only significant effect was a significant difference between groups for supraspinatus muscle thickness at 6 months post-surgery. The Stromberg study did not have a measure for muscle size.

When comparing the three cross-education studies that applied unilateral training to the injured limb, the wrist fracture study (Study 4 in thesis) had the most promising results. Briefly, the study suggested that cross-education improved strength and AROM of the fractured limb after unilateral training the non-fractured limb, with non-significant trends for improvements in patient-rated functional scores. The cross-education intervention appeared to have a more profound impact on rehabilitation in the wrist fracture study compared to the shoulder surgery study. Although the reason for the differences between these studies is unknown, shoulder surgery may not be an ideal model to use due to the long duration from the time of the injury to

the time of the surgery. As was discussed in the shoulder surgery study, there is typically a very long wait (i.e. months to years) from the time of the injury to the time of the surgery. During this time, the injured side would have undergone many negative effects on the muscle, and by the time the surgery finally occurred, the muscle already would have experienced large negative changes in the anatomy and function. In contrast to the shoulder surgery model, the wrist fracture model is characterized by a rapid response to an injury event and the fracture is immediately reduced to begin rehabilitation. The timing from the fracture to casting could vary from a few hours to a few days in most scenarios, whereby there would be very little time for anatomical changes in the muscle from the time of fracture to the time of casting. However, owing to the difference in timing from injury to casting, the short-term impact of the immobilization on the affected limb may be more drastic in the wrist fracture model. Previous disuse studies have shown a more drastic effect on the muscle in the early phase of long-term bed rest or immobilization (Dittmer & Teasell, 1993; Bloomfield, 1997). Nearly half of normal strength is lost within 3-5 weeks of immobilization (Dittmer & Teasell, 1993), with dramatic changes in muscle mass occurring after 4-6 weeks of bed rest (Bloomfield, 1997). This difference in timing may ultimately affect the potential for cross-education to benefit rehabilitation in the injured limb. If cross-education were applied immediately after a shoulder injury (i.e. prior to the participant knowing they would receive shoulder surgery), there could potentially be a greater effect of cross-education. Possibly the greatest cross-education effect would be shown in shoulder injuries if the unilateral strength training on the non-injured limb began immediately after the injury, continued up to the surgery, and throughout the post-surgery rehabilitation phase.

Another reason why there was a difference in the findings between the wrist fracture

study and the shoulder surgery study may be due to differences in and variability of treatment, and the age and demographics of the participants. In the wrist fracture study, the participants were all women over 50 years of age who had a distal radius fracture. The rehabilitation after distal radial fractures was standardized, beginning with immobilization in a cast for 6 weeks, followed by ROM exercises, and strengthening. A limited number of participants had surgery on their wrist, and some attended elective physiotherapy from a therapist of their choice. Both surgery and physiotherapy would increase the variability in recovery; however, the injury itself and the rehabilitation were quite standard across participants. In the shoulder surgery study, the participant characteristics, the injury, and the rehabilitation were much more variable. The study included both males and females of all ages (range from 21 to 83 years), included rotator cuff tears on any cuff muscle and of any size, included Bankart repairs, and included patients from 3 surgeons and multiple physiotherapists. The variability in the shoulder surgery study likely reduced the potential to detect cross-education effects with the given sample size. If the shoulder surgery study used a more homogenous sample (i.e. only included the same size of rotator cuff tear, limited to males or females, determined age range), it could have possibly shown different results.

It remains possible that there was simply little or no advantage for cross-education training after shoulder surgery. The only significant benefit of the intervention was for supraspinatus muscle thickness at 6 months post-surgery, with no benefits for strength, AROM, or the WORC. Although all evidence in model immobilization cross-education studies suggests there is a benefit to the injured limb, the exact mechanism for cross-education in model immobilization settings may be different than in a real injury setting, and may differ between wrist fracture rehabilitation and shoulder surgery rehabilitation. The shoulder injury itself may

have effects on the muscle that may not show the transfer in strength to the injured limb.

Now that there is evidence from three separate cross-education studies that have applied unilateral strength training to the injured limb, what can be concluded from the literature? It can be concluded that there is some evidence for a cross-education effect to an injury setting; where unilateral strength training can lead to improved strength, AROM and muscle thickness when looking at the results from the studies pooled. Although there are positive changes in objective measures (i.e. strength and AROM), it is difficult to determine if improved objective measurements lead to improved function or rehabilitation of the injured limb that can make a significant difference in day-to-day tasks.

One way of interpreting clinical data may be to determine the minimal clinically important difference (MCID). The MCID of an outcome measure is the minimum change in a score that indicates a meaningful difference for the patient (Smith et al., 2012). For example, if the MCID for a measure is 15 points and a participant has a change of 20 points, this would indicate a true clinical change for the participant. The MCID can be calculated for specific outcome scores, and has been identified as a change in 245 points (11.7%) for the WORC questionnaire (Smith et al., 2012), and a change in 24 points (16%) for the PRWE (Schmitt & Di Fabio, 2004). For handgrip strength, the MCID has been identified as 6 kg (Nitschke et al., 1999), and for ROM the MCID was shown to be 13.5 degrees (Witthaut et al., 2011). The minimal clinically important difference can be useful in detecting small but important changes in patient status, yet it is seldom used to compare responsiveness across outcome measures (Schmitt & Di Fabio, 2004). There is clearly a gap in the literature in determining which methods to use in assessing improvements in rehabilitation, and future studies may look further into assessing patient differences using the minimal clinically important difference.

Application of cross-education after unilateral injuries has improved strength, AROM and muscle size; however, we do not have any measures of the effects on bone strength or muscle activation. Cross-education could potentially impact bone strength, and therefore could help prevent re-injury. If it could be shown that unilateral strength training of the healthy limb improves bone strength in both the healthy and injured limb after a fracture, there would be even larger implications for applying cross-education into clinical settings. In wrist fractures for example, the population at the highest risk for fracture is older women (Handoll et al., 2006). This population already has a decline in bone strength, and if a strength training program was implemented after a unilateral wrist fracture, it may help slow the decline in bone strength, and could potentially help prevent re-fracture. Cross-education may also impact muscle recruitment of the injured limb after unilateral strength training of the non-injured limb. Strength training of the non-injured limb may increase the activation in the muscles of the injured limb via cross-education. Increased muscle activation may in turn lead to improved muscle recruitment when executing a task, and could be clinically relevant if it improved participants' ability to complete day-to-day activities. The impact of cross-education on other clinically relevant physiological components such as bone strength and muscle activation are important to identify.

Cross-education may also be applied in other clinical settings, such as after stroke. The first study to apply cross-education to stroke rehabilitation has recently been published (Dragert and Zehr, 2012). The study investigated if unilateral dorsiflexion training of the less affected limb could increase strength and motor output in the trained and untrained limbs following stroke. Results showed that the trained and untrained limbs improved strength by 34% and 31%, respectively. Importantly, four participants who were unable to generate force on the more affected side prior to training were able to after training of the less affected side. This study

provides the first evidence of a beneficial effect in stroke rehabilitation; however, there are limitations to the study such as not including a control group. Although this study provides promising evidence, more research should be conducted in the area.

6.4 Mechanisms of Cross-Education

Although none of the thesis studies focused on mechanisms of cross-education, it is important to consider what mechanisms may contribute to cross-education in model immobilization settings and in real injury settings. The most recent literature suggests that cross-education may be due to decreased interhemispheric inhibition (Hortobágyi et al., 2011). Hortobágyi et al. (2011) greatly advanced the literature on cross-education mechanisms, but the study was conducted in healthy, non-immobilized participants. In model immobilization settings, the cross-education effect to the immobilized limb has been associated with an increase in the volume of activation in the contralateral motor cortex (Farthing et al., 2011) and a maintenance in corticospinal excitability (Pearce et al., 2012). The results of the model immobilization studies provide evidence of a cortical mechanism to cross-education, yet there are no studies that have investigated mechanisms of cross-education after an injury.

We can only speculate on the mechanisms of cross-education in an injury setting. The mechanism in a clinical setting may be the same mechanism that occurs in studies using healthy participants and in model immobilization studies. There is likely a cortical component causing the transfer to the injured limb, but there may also be other contributors such as muscle mechanisms that cause the cross-education effect. The studies on muscle mechanisms in healthy participants have not shown a strong link (Hortobágyi et al., 1997; Evetovich et al., 2001; Farthing et al., 2005), but they may play a more prominent role in real injury settings, and should

not be ruled out. There has been very little research conducted on the contribution of the spine, which may also contribute to the transfer considering the connectivity between the brain and the muscles. The most prominent theory may be that there is a combination of mechanisms, including interhemispheric inhibition that work together to produce cross-education effects. Very little is known about the mechanisms, especially in an injury setting, and investigations should continue in this area.

6.5 Clinical Application of Study Findings

Cross-education has shown potential for application to injury settings; however, it is likely not yet ready to be implemented into clinics. Although there is no perceived harm to participants in completing a strength training program on their non-injured limb, more evidence from well-controlled and larger scale intervention studies is needed to determine if unilateral strength training provides a consistent benefit to the injured limb that is cost effective for the health care system. If cross-education were implemented into rehabilitation settings, it would need to be implemented at the doctor level, and further supported by physiotherapists and exercise therapists who design the exercise programs. Depending on the type of injury, patients may first see a doctor and may not see a physiotherapist or exercise therapist until weeks after the injury, or they may not see them at all. For wrist fracture rehabilitation in the clinic where participants in Study 4 were recruited, patients saw the doctor immediately after the fracture, the cast was applied, and the patient came back for follow-up visits at 3 weeks, 6 weeks, 9 weeks and 12 weeks. Most patients were not referred to physiotherapy, and the ones that were referred did not get the referral until 9 or 12-weeks post-fracture. Based on the current rehabilitation protocols following wrist fractures, if cross-education were implemented into clinics, the training

program would need to be given at the initial visit to the doctor clinic. It may not be feasible to have doctors give strength training programs to patients during clinic visits due to extra time needed for each visit; therefore additional rehabilitation staff would be needed to teach the training programs to patients. Potentially, Canadian Society for Exercise Physiology - Certified Exercise Physiologists (CEP) could be integrated into clinical settings to teach patients the strength training program and follow-up with progressions in training. Patients would also likely need to be given a strength training device (i.e. handgrip trainer) in order for them to follow the program. Physiotherapists would need to be educated on the benefits of cross-education after injuries so they could continue the training program as they began their treatment.

It may not be feasible to implement cross-education into clinics at this point in time due to the cost of hiring additional staff to implement the training program and the structure of the current rehabilitation protocols. However, given the substantial yearly cost of treating fragility fractures was 2.3 billion dollars in Canada in 2010 (Tarride et al., 2012), of which distal radius fractures account for the largest portion (Brogren et al., 2011; TimoBeil et al., 2011), the cost of additional staff to implement cross-education interventions may be offset by reducing the long-term cost of treatment owing to a more complete and expedited recovery.

Implementing cross-education into rehabilitation settings may be limited by the specific injuries it targets. Cross-education may not be applicable to injuries that would affect the neck or core musculature, for example due to the unilateral nature of the phenomenon. The current literature suggests that cross-education is limited to unilateral injuries.

If implementing a cross-education training program, the healthy extremity needs to be able to successfully carry out the training. In the shoulder surgery study, multiple participants were excluded due to shoulder pathology on both the non-surgical limb and surgical limb, as

they would have not been able to complete the volume of training that was required for the training program. In order to include participants with pathology affecting the non-surgical limb, strength training programs could be given on an individual basis, whereby a patient with an injury on both sides would have a training program that was suited to their specific needs and capabilities. The training program would need to have enough resistance that it could improve strength on the training limb, without causing any more harm to the previous injury. Cross-education may be feasible to implement after injuries that have both sides affected, in the context of a more global strengthening and program, given there is educated rehabilitation staff to determine what type of training program is appropriate for the individual.

In order for cross-education to be successfully implemented, the entire rehabilitation team (i.e. doctors, physiotherapists, and exercise therapists) would need to agree in the treatment program, and make it a standard protocol. The structure of the rehabilitation would ideally consist of 5 steps: 1. The injury occurs; 2. The patient sees the doctor, the injury is assessed and the treatment is determined; 3. The patient is referred to a physiotherapist immediately after the injury to determine if a strength training program can be completed on the individual's non-injured limb, and to determine which exercises can be prescribed; 4. The patient is referred to a CEP to implement the strength training program; 5. The patient is continually monitored for recovery of the injured limb, and for progression in the strength training program by all rehabilitation staff. In order for this 5 step rehabilitation program to occur, a change needs to happen in the current structure, with a team approach to recovery and early referral to physiotherapists and exercise physiologists. It may be more feasible and beneficial for patient recovery if cross-education is implemented as part of a global conditioning and strengthening rehabilitation program designed to improve overall health outcomes of patients experiencing

significant unilateral injuries.

6.6 Limitations

One of the major limitations of the thesis was the inability to control for all parameters in the clinical studies. We were unable to control for the specific physiotherapy programs that individuals were given for the rehabilitation on their injured limb, and were unable to control for factors in participants' daily lives (i.e. work demands) that may have affected their recovery. The clinical interventions also included follow-up calls every 2-weeks to all participants. The follow-up calls may have influenced the outcome since it is not part of the standard rehabilitation protocol for patients. In addition, it was very difficult to have all testers blinded to the group randomization and it was impossible to have the participants blinded to their groupings due to the nature of strength training interventions.

Another limitation of the research was that there was no direct evidence for cross-education to improve clinical function despite evidence for improved strength, AROM and muscle thickness. Arguably, strength, AROM and muscle size are determinants of function; however, not demonstrating changes in measures that are commonly used in clinical settings, such as the PRWE, questions the relevance of applying cross-education to injuries. This is a limitation of the work and perhaps more sensitive tools are needed to determine functional changes.

The thesis studies are also limited in the generalizability of the research. The studies focused on the upper body only, and more specifically only investigated shoulder and the wrist. The findings may be generalized to other upper body immobilization models or injuries, but should not be generalized to the lower body. In addition, the wrist fracture study only recruited

women over the age of 50 years. The findings may be generalized to other older women who have upper limb fractures, but it may not be suitable to assume the same results for men or for those younger than 50 years old.

Another limitation of the thesis is that the studies had relatively small participant numbers. Cross-education studies have shown significant cross-education effects in healthy participants with subject numbers as low as 7 (Farthing et al., 2011) and 10 (Farthing et al., 2009) participants per group. Study 1 in the thesis found significant effects with as low as 8 participants per group, and the Study 2 found significant effects with 10 participants per group. When applying cross-education to shoulder surgery participants in Study 3, power calculations provided an estimate of 21 participants per group needed to detect a 10% difference between groups; however, only 20 participants total were recruited. For the wrist fracture study, we estimated 18 participants per group, and the final analysis included 18 participants in the training group and 21 participants in the control group. We did not meet the target number of participants in the shoulder surgery study, which may have contributed to the non-significant differences, but we did find significant differences in the wrist fracture study. Although the wrist fracture study showed an improvement at 12 weeks post-fracture, the sample size was quite small.

If the sample sizes were larger in the studies, it would have also permitted analyses with more detailed comparisons between sub-groups. For example, in the shoulder surgery study, an analysis could have been conducted comparing outcome of those who waited less than a year for their surgery and those who waited over a year. In the wrist fracture study, an analysis could have been conducted comparing outcome of those who were treated with casting only, compared to those who were casted and also had surgery. There are multiple analyses that could have been

carried out if the sample sizes permitted; however, the thesis studies were the first to apply cross-education to a variety of different clinical settings, and therefore the findings further contribute to the literature despite these limitations.

Another limitation of the studies was the impact of dropouts. Most of the participants dropped out of the studies due to the time commitment of the strength training interventions and the time commitment of follow-up testing procedures. Dropouts were inevitable, yet may have influenced the results by excluding their data from final analyses. Dropouts were excluded in the analyses due to the preliminary nature of the work in clinical settings.

Being involved in a research study with a strength training intervention may have impacted the control groups in the thesis, and is therefore a potential limitation. Low intensity training with contractions as low as 10% maximal voluntary contraction have been shown to increase strength (Laidlaw et al., 1999). As mentioned previously, even training with imagined contractions at high volume can elicit strength gains (Yue and Cole, 1992). There is potential that participants engaged in some additional training that influenced recovery parameters differently than what might be expected in a normal recovery setting. Therefore, the control group may not have truly represented the response to “standard rehabilitation”. This is a potential limitation of many controlled intervention studies in clinical settings where all groups are tested at regular follow-up intervals. Arguably this type of confound might actually decrease the magnitude of differences between intervention and control groups in clinical intervention studies such as included in the current thesis.

Finally, the studies were also limited due to the short-term follow-up. Beginning with the shoulder sling model immobilization study (Study 1), the follow-up was only 4 weeks long. Similarly, the shoulder cross-education resistance tubing training study (Study 2) in healthy

individuals was 4 weeks in duration, and we cannot be certain of any sustained effects after a 1-month period of time. In both the shoulder surgery study (Study 3) and the wrist fracture study (Study 4), participants were followed for 6 months. At the end of the 6 month duration, participants in the shoulder surgery study and the wrist fracture study were not fully recovered. The effect of cross-education on the long-term outcome after an injury is not known. Perhaps if the participants continued with the exercise program for 1 year, they would be fully recovered and we would have a better understanding of the long-term effects of cross-education after injuries.

6.7 Future Research

The thesis findings have greatly added to the literature on cross-education, but have also raised many more questions. Future research could focus on applying cross-education to other types of injury settings, such as other upper limb injuries (i.e. humerus fractures) or lower body injuries (i.e. knee replacements). If applying cross-education in the lower body and it should be noted that early weight-bearing and strengthening of the injured limb is important to improve function; therefore cross education in the lower body may not have the same implications as it does in the upper body. One study that needs to be completed is to determine if there is cross-education direction of the effect in the lower body. Farthing et al. (2005) conducted this study in the upper body, but we still don't know what effect, if any, limb dominance has in the lower limbs for cross-education. Future studies could also investigate the effects of cross-education in lower body model immobilization settings, and this might be the most important next step before a clinical cross-education study is implemented in a lower limb unilateral injury setting. For example, a study could use a healthy (i.e. non-injured) population and place the foot in a cast, or

walking boot, while applying a strength training program on the non-immobilized limb. There is also no prior work done applying cross-education to the lower limb in injury settings. Injuries such as knee surgeries could be used to determine if there are any beneficial effects of cross-education to the surgical limb.

Future studies could continue applying cross-education to shoulder surgeries, but could investigate a more homogenous and larger sample. For example, a study could recruit only shoulder surgery participants with large rotator cuff tears or only include participants who have been waiting for surgery for less than one year. An additional shoulder surgery study could apply cross-education strength training immediately after the shoulder injury occurred, could continue strength training of the uninjured limb up to the surgery, and apply cross-education throughout the follow-up post-surgery. It would be very interesting to see if cross-education would produce any beneficial effects in a shoulder surgery study conducted in this way; however, it would be a long-term study that would be a large commitment for the participants and would require significant funding to undertake.

Other cross-education studies could determine if there is a direction of effect for cross-education in an injury setting. In light of previous data demonstrating a larger cross-education effect from the dominant to non-dominant arm direction in healthy participants (Farthing et al., 2005), there may be greater potential for cross-education in the context of a non-dominant arm injury. A study could be conducted that recruits only right-handed participants, and compares the effect of cross-education on left-handed fractures, and right-handed fractures. This could also be investigated in the lower limbs to determine if there would be any differences in the response between the upper and the lower body.

Future investigations could also include large randomized controlled trials with long-term

follow-up. These studies could be multi-site with a variety of clinics involved. A good model to use would be distal radial fractures since there is preliminary evidence suggesting beneficial effects at 12 weeks post-fracture, and the injury and rehabilitation is more standardized compared to other injuries such as shoulder surgeries. Other studies could conduct follow-up measures at more frequent time points after the acute stage of recovery (i.e. at 9, 10, 11 and 12-weeks post fracture for distal radial fractures). Studies could also investigate new ways of measuring function, such as creating self-report questionnaires that are specific to injuries on the dominant and non-dominant limbs. Activities of daily living may also be measured to determine if cross-education has an impact on daily life.

Lastly, future cross-education studies could investigate other outcomes such as bone strength, and muscle recruitment after injuries. To measure bone strength, peripheral quantitative computed tomography (pQCT) could be used in the injured limb immediately after the injury, and at consecutive follow-ups. To measure muscle recruitment, EMG could be used to get an estimate of muscle activation during strength tests following the injury. Interpolated twitch could also be used to determine the percent activation in the muscles during strength tests. In addition, other methods of assessing muscle size, such as MRI could be used to determine changes throughout recovery.

6.8 Conclusion

The major conclusion of this project was that there is potential for cross-education to improve recovery after unilateral injuries; however, more research needs to be done to further determine if these effects can be replicated in other clinical settings. There was evidence for cross-education to benefit a healthy immobilized limb using a shoulder sling model, and

evidence that a clinically relevant shoulder strength training program can produce cross-education effects in the untrained limb. When cross-education was applied to shoulder surgeries, there were improvements in muscle size, but no effects on strength, AROM or the WORC questionnaire. In comparison, when cross-education was applied to wrist fractures, strength and AROM improved for the injured limb. The findings from Study 1 and 2 provide further evidence that cross-education may be beneficial in clinical settings. Studies 3 and 4 are the first well-controlled studies that applied cross-education to real orthopaedic injuries, and are the first studies to present evidence that cross-education benefits the early stages of rehabilitation after an injury. The results may have potential to change the current rehabilitation protocols following unilateral injuries, but more evidence is needed in a variety of clinical settings to further investigate the effects of cross-education. The thesis studies have made an important advancement in cross-education literature, and provide evidence that cross-education may be beneficial to unilateral orthopaedic injury rehabilitation.

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Appendices

Appendix A: Certificate of Approval Experiment 1



Certificate of Approval Study Amendment

PRINCIPAL INVESTIGATOR

Jonathan P. Farthing

DEPARTMENT

Kinesiology

Bo #

08-155

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUTCollege of Kinesiology
87 Campus Drive
Saskatoon SK S7N 5B2**STUDENT RESEARCHER(S)**

Charlene Magnus

SPONSORING AGENCIES

NATURAL SCIENCES & ENGINEERING RESEARCH COUNCIL OF CANADA (NSERC)

TITLE

Can Cross-Education Attenuate Muscle Strength and Muscle Size in the Biceps and Triceps after a Four-Week Period of Immobilization?

APPROVAL OFAddition of Medically Cleared Injured Study Subjects
Research Participant Information and Consent Form (16-Jul-2009)**APPROVED ON**

17-Jul-2009

CURRENT EXPIRY DATE

02-Sep-2009

REVIEW TYPEDelegated Review: ☒ Full Board Meeting: ☐**CERTIFICATION**

The study is acceptable on scientific and ethical grounds. The Bio-REB considered the requirements of section 29 under the Health Information Protection Act (HIPA) and is satisfied that this study meets the privacy considerations outlined therein. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL

The University of Saskatchewan Biomedical Research Ethics Board reviews above minimal studies at a full-board (face-to-face) meeting. Any research classified as minimal risk is reviewed through the delegated (subcommittee) review process. The initial Certificate of Approval includes the approval period the REB has assigned to a study. The Status Report form must be submitted within one month prior to the assigned expiry date. The researcher shall indicate to the REB any specific requirements of the sponsoring organizations (e.g. requirement for full-board review and approval) for the continuing review process deemed necessary for that project. For more information visit http://www.usask.ca/research/ethics_review/.

REB ATTESTATION

In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. This approval and the views of this REB have been documented in writing.

Appendix B: Certificate of Approval Experiment 2 and 3



Certificate of Approval Study Amendment

PRINCIPAL INVESTIGATOR
Jonathan P. Farthing

DEPARTMENT
Kinesiology

Bio #
11-28

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT
College of Kinesiology
87 Campus Drive
Saskatoon SK S7N 5B2

STUDENT RESEARCHER(S)
Charlene Magnus

FUNDER(S)
NATURAL SCIENCES & ENGINEERING RESEARCH
COUNCIL OF CANADA (NSERC)

TITLE

: Does Strength Training the Non-Injured Limb Improve Rehabilitation for the Injured Limb After Shoulder Injury?

APPROVAL OF

APPROVED ON

CURRENT EXPIRY DATE

Amendment to Study:

23-May-2011

21-Mar-2012

-Addition of non-surgical, non-strength training control group

-Removing objective functional tests

-Modifying the strength training program's number of
contractions

-Decreasing the number of strength tests and range of motion
tests

Subject Information and Consent Form (19-May-2011)

Delegated Review ☒ Full Board Meeting ☐

CERTIFICATION

The study is acceptable on scientific and ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL

The University of Saskatchewan Biomedical Research Ethics Board reviews above minimal studies at a full-board (face-to-face meeting). Any research classified as minimal risk is reviewed through the delegated (subcommittee) review process. The initial Certificate of Approval includes the approval period the REB has assigned to a study. The Status Report form must be submitted within one month prior to the assigned expiry date. The researcher shall indicate to the REB any specific requirements of the sponsoring organizations (e.g. requirement for full-board review and approval) for the continuing review process deemed necessary for that project. For more information visit http://www.usask.ca/research/ethics_review/.

REB ATTESTATION

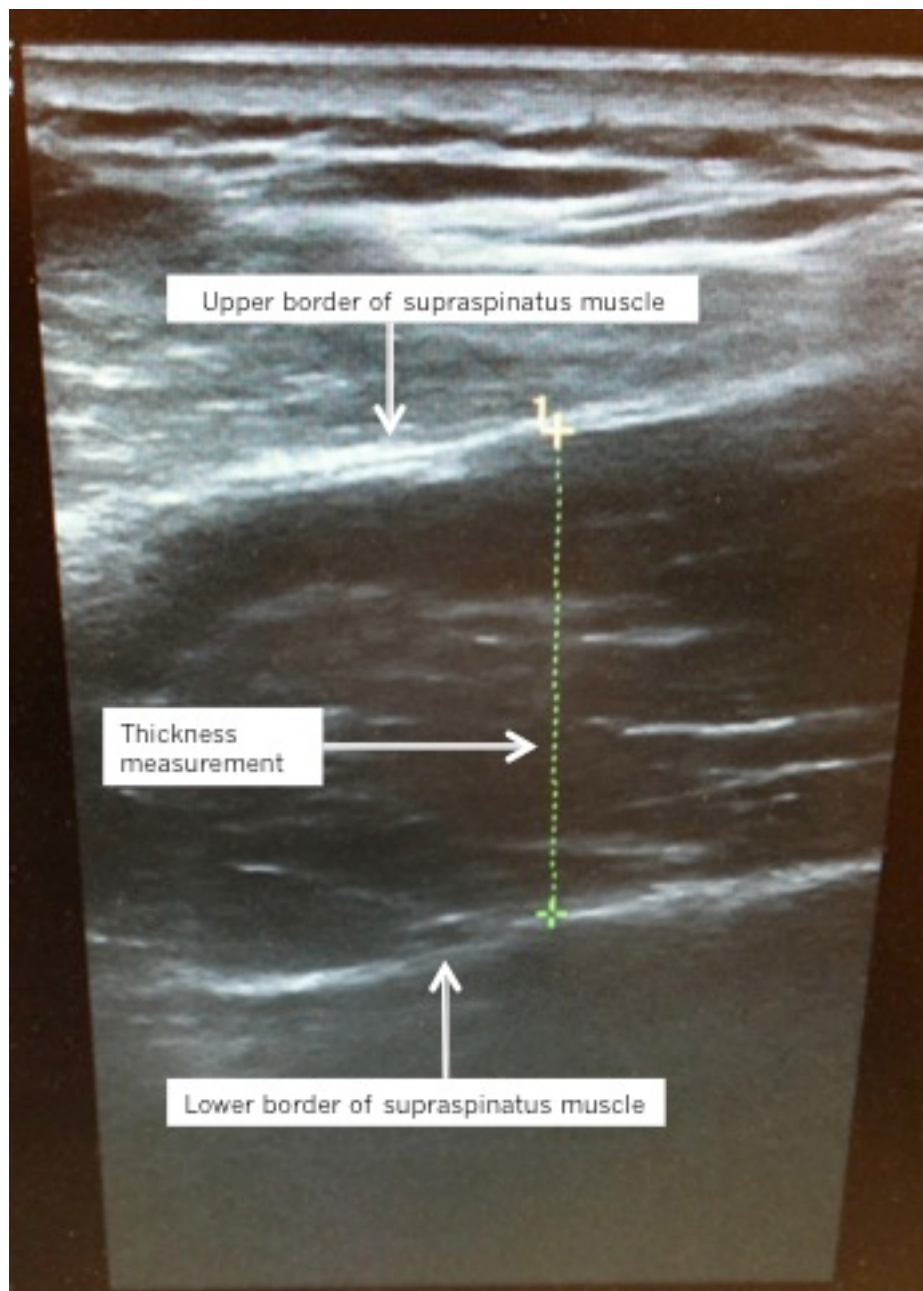
In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. This approval and the views of this REB have been documented in writing.

Appendix C: Shoulder Strength Testing Positions



Figure 1: Shoulder external rotation; Figure 2: Shoulder internal rotation; Figure 3: Scaption

Appendix D: Muscle Thickness Measure for Supraspinatus



Appendix E: Western Ontario Rotator Cuff (WORC) Index



WESTERN ONTARIO
ROTATOR CUFF INDEX
(WORC)[®]

**A disease-specific quality of life measurement tool for patients
with rotator cuff disease**

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All rights reserved. No part of this measurement tool may be reproduced or transmitted in any form or by any means electronic, mechanical, including photography, recording, or any information storage or retrieval system – without permission of the copyright holder. Permission to reproduce the WORC scoring algorithm is hereby granted to the holder of this tool for his/her personal use.

Suggested citation: The Development and Evaluation of a Disease-Specific Quality of Life Measurement Tool for Rotator Cuff Disease: The Western Ontario Rotator Cuff Index , American Academy of Orthopaedic Surgeon's Annual Meeting Book of Abstracts, 1998.

INSTRUCTIONS TO PATIENTS

In the following questionnaire you will be asked to answer questions in the following format and you should give your answer by putting a slash "/" on the horizontal line.

NOTE:

1. If you put a slash "/" at the left end of the line i.e.



then you are indicating that you have no pain.

2. If you put your slash "/" at the right end of the line i.e.



then you are indicating that your pain is extreme.

3. Please note:

a) that the further to the right you put your slash "/", the more you experience that symptom.

b) that the further to the left you put your slash "/" , the less you experience that symptom.

c) please do not place your slash "/" outside the end markers

You are asked to indicate on this questionnaire, the amount of a symptom you have experienced in the past week as related to your problematic shoulder. If you are unsure about the shoulder that is involved or you have any other questions, please ask before filling out the questionnaire.

If for some reason you do not understand a question, please refer to the explanations that can be found at the end of the questionnaire. You can then place your slash "/" on the horizontal line at the appropriate place. If an item does not pertain to you or you have not experienced it in the past week, please make your "best guess" as to which response would be the most accurate

Section A: Physical Symptoms
INSTRUCTIONS TO PATIENTS

The following questions concern the physical symptoms you have experienced due to your shoulder problem. In all cases, please enter the amount of the symptom you have experienced in the last week. (Please mark your answers with a slash "/")

1. How much sharp pain do you experience in your shoulder?

no pain |-----| extreme pain

2. How much constant, nagging pain do you experience in your shoulder?

no pain |-----| extreme pain

3. How much weakness do you experience in your shoulder?

no weakness |-----| extreme weakness

4. How much stiffness or lack of range of motion do you experience in your shoulder?

no stiffness |-----| extreme stiffness

5. How much are you bothered by clicking, grinding or crunching in your shoulder?

none |-----| extreme

6. How much discomfort do you experience in the muscles of your neck because of your shoulder?

no discomfort |-----| extreme discomfort

SECTION B: Sports/Recreation
INSTRUCTIONS TO PATIENTS

The following section concerns how your shoulder problem has affected your sports or recreational activities in the past week. For each question, please mark your answers with a slash "/".)


7. How much has your shoulder affected your fitness level?

not affected  extremely affected

8. How much difficulty do you experience doing push-ups or other strenuous shoulder exercises because of your shoulder?

no difficulty  extreme difficulty

9. How much has your shoulder affected your ability to throw hard or far?

not affected  extremely affected

10. How much difficulty do you have with someone or something coming in contact with your affected shoulder?

no fear  extremely fearful

SECTION C: Work
INSTRUCTIONS TO PATIENTS

The following section concerns the amount that your shoulder problem has affected your work around or outside of the home. Please indicate the appropriate amount for the past week with a slash "/".

11. How much difficulty do you experience in daily activities about the house or yard?



12. How much difficulty do you experience working above your shoulder?



13. How much do you use your uninvolved arm to compensate for your injured one?



14. How much difficulty do you experience lifting heavy objects at or below shoulder level?



SECTION D: Lifestyle

INSTRUCTIONS TO PATIENTS

The following section concerns the amount that your shoulder problem has affected or changed your lifestyle. Again, please indicate the appropriate amount for the past week with a slash "/".

15. How much difficulty do you have sleeping because of your shoulder?

A horizontal scale with vertical tick marks at both ends. Below the left tick mark is the text "no difficulty". Below the right tick mark is the text "extreme difficulty".

16. How much difficulty have you experienced with styling your hair because of your shoulder?

A horizontal scale bar with vertical end caps. Below the left end cap is the text "no difficulty". Below the right end cap is the text "extreme difficulty".

17. How much difficulty do you have "roughhousing or horsing around" with family or friends?

18. How much difficulty do you have dressing or undressing?

[illegible]

SECTION E: Emotions
INSTRUCTIONS TO PATIENTS

The following questions relate to how you have felt in the past week with regard to your shoulder problem. Please indicate your answer with a slash "/".

19. How much frustration do you feel because of your shoulder?

no |-----| extreme
frustration | frustration

20. How "down in the dumps" or depressed do you feel because of your shoulder?

none |-----| extreme

21. How worried or concerned are you about the effect of your shoulder on your occupation?

not at |-----| extremely
all | concerned

**An Explanation of the Meaning of the Questions in the Western Ontario Rotator Cuff Index
WORC**

Section A: Physical Symptoms

Question 1.

Refers to pain in your shoulder that is quick and sudden or that you might refer to as a catching type of pain.

Question 2.

Refers to the dull background ache that always seems to be there as opposed to the sharp pain that is referred to in question 1.

Questions 3.

Refers to a lack of strength to carry out a movement.

Question 4.

Refers to the feeling of the joint not wanting to move. This is often experienced in the morning upon rising, after exercise or after a period of inactivity. It could also refer to not having full movement of your shoulder in all or any direction(s).

Question 5.

Refers to any of these sounds or feelings that you experience in your shoulder with any type of movement.

Question 6.

Refers to the amount of tension, pain or spasm that you experience in the muscles of your neck that seems to be caused by your shoulder problem.

Section B: Sports/Recreation

Question 7.

Refers to the fitness level you maintained before your shoulder became a problem. Include a decrease in muscle tone or strength level, cardiovascular fitness or strength level.

Question 8

Refers to any overhead activity requiring you to use some force in its execution. If you do not throw a ball, please consider any other activity such as spiking in volleyball, throwing a stick to your dog, swimming the front crawl, serving in tennis, etc.

Question 9.

Please consider whenever you have been afraid or wary of someone or something hitting or coming into contact with your affected shoulder such as in a sport, a crowded room, an elevator or someone slapping your shoulder in a greeting .

Question 10.

Refers to any exercise requiring you to put force on your shoulder such as push-ups, bench press etc.

Section C: Work

Question 11.

This refers to activities such as raking, shoveling, vacuuming, dusting, weeding, hoeing and washing windows or floors etc.

Question 12.

Refers to any activity requiring you to raise your arms above shoulder level ie. putting dishes in a cupboard, reaching for an object, painting a ceiling or painting above shoulder level etc.

Explanation of Questions cont.

Question 13.

Refers to if you now use your other arm for any activity or work where you would ordinarily have done it with the arm on the problematic side. If your other shoulder is also symptomatic from Rotator Cuff Disease or some other disease, then consider how you would answer the question if that shoulder was normal.

Question 14.

This does not refer to lifting above your head but to lifting any heavy objects below shoulder level e.g. a bag of groceries, case of pop, suitcase, equipment at work, books, etc.

Section D: Lifestyle

Question 15.

Refers to having to change your sleeping position, waking up during the night, trouble getting to sleep or waking up feeling unrested.

Question 16.

Refers to anything that you would do to your hair such as combing, brushing or washing that requires you to reach up with your problematic arm.

Question 17.

Refers to any type of rough or vigorous play activity that you would normally engage in with your family or friends.

Question 18.

Refers to reaching behind to do up or undo a zipper or button(s), do up or undo a bra, pulling on or removing a sweater or top over your head, or tucking in a shirt or top.

Section E: Emotions

Question 19.

Refers to the frustration you feel because of your inability to do things you used to do or that you want to do but can't.

Question 20.

Down-in-the-dumps or depressed is self-explanatory

Question 21.

Refers to worrying about your shoulder getting worse instead of better or staying the same and being concerned about what effect that will have on your occupation or work (consider work inside or outside the home).

SCORING OF THE WESTERN ONTARIO ROTATOR CUFF (WORC) INDEX

1. Measure the distance from the left side of the line and calculate the score out of 100 (recorded to the nearest 0.5 mm). Write it into the space provided for that question.
2. You can calculate a total score for each domain (Physical Symptoms/600; Sports and Recreation/400; Work/400 and Lifestyle/400; Emotions/400) or the total score for the domains can be summed for an aggregate score out of 2100.
3. Some find it more meaningful to report scores out of 100 i.e. a percentage of normal score. Since the worst possible score is 2100, the aggregate score is subtracted from 2100 and divided by 21. e.g. if your patient's total aggregate score = 1625; then the percentage score would be $\frac{2100 - 1625}{21} = 22.6\%$

The same applies for each domain.

physical symptoms

PS 1	.
PS 2	_____.
PS 3	.
PS 4	_____.
PS 5	_____.
PS 6	.
TOTAL	

sports/recreation

S 7	_____.
S 8	_____.
S 9	.
S 10	_____.
TOTAL	

work

W11	_____.
W12	.
W13	.
W14	_____.
TOTAL	

lifestyle

L 15	.
L 16	_____.
L 17	.
L 18	_____.
TOTAL	

emotions

E 19	.
E 20	_____.
E 21	_____.
TOTAL	

summary

PS	.
S	_____.
W	_____.
L	.
E	_____.
TOTAL:	

Appendix F: Mini-Cog Assessment Instrument for Dementia

INSTRUCTIONS FOR ADMINISTRATION

The Mini-Cog Assessment Instrument for Dementia

The Mini-Cog assessment instrument combines an uncued 3-item recall test with a clock-drawing test (CDT). The Mini-Cog can be administered in about 3 minutes, requires no special equipment, and is relatively uninfluenced by level of education or language variations.

Administration

1. Instruct the patient to listen carefully to and remember 3 unrelated words and then to repeat the words.
2. Instruct the patient to draw the face of a clock, either on a blank sheet of paper, or on a sheet with the clock circle already drawn on the page. After the patient puts the numbers on the clock face, ask him or her to draw the hands of the clock to read a specific time, such as 11:20. These instructions can be repeated, but no additional instructions should be given. Give the patient as much time as needed to complete the task. The CDT serves as the recall distractor.
3. Ask the patient to repeat the 3 previously presented word.

Scoring

Give 1 point for each recalled word after the CDT distractor. Score 1–3.

A score of 0 indicates positive screen for dementia.

A score of 1 or 2 with an abnormal CDT indicates positive screen for dementia.

A score of 1 or 2 with a normal CDT indicates negative screen for dementia.

A score of 3 indicates negative screen for dementia.

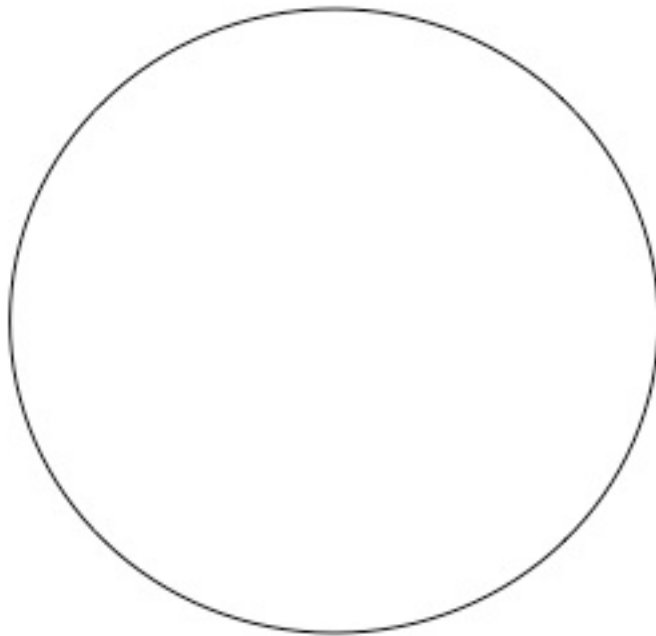
Borson S, Scanlan J, Brush M, Vitaliano P, Dokmak A. The mini-cog: a cognitive “vital signs” measure for dementia screening in multi-lingual elderly. *Int J Geriatr Psychiatry* 2000;15(11):1021–1027.

The CDT is considered normal if all numbers are present in the correct sequence and position,
and the hands
readably display the requested time.

CLOCK DRAW TEST

INSTRUCTIONS:

1. Inside the circle, please draw the hours of a clock as they normally appear
2. Place the hands of the clock to represent the time: “ten minutes after eleven o’clock”



Appendix G: Certificate of Approval: Experiment 4



Biomedical Research Ethics Board (Bio-REB)

Certificate of Re-Approval

PRINCIPAL INVESTIGATOR

Jonathan P. Farthing

DEPARTMENT

Kinesiology

Site #

10-17

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT

College of Kinesiology

Royal University Hospital

87 Campus Drive

103 Hospital Drive

Saskatoon SK S7N 5B2

Saskatoon SK S7N 0W8

SUB INVESTIGATOR(S)

Cathy Arnold, G. E. Johnson, Vanina Dal Bello-Haas, Jenny Bazran

STUDENT RESEARCHER(S)

Charlene Magnus

FUNDER(S)

NATURAL SCIENCES & ENGINEERING RESEARCH

COUNCIL OF CANADA (NSERC)

ROYAL UNIVERSITY HOSPITAL FOUNDATION

TITLE

CAST - Cross-training of Arm Strength Training Trial: Does cross-training improve function and reduce risk of future falls and fracture in the first year following a distal radial fracture?

RE-APPROVED ON

24-Apr-2012

EXPIRY DATE

23-Apr-2013

Delegated Review: ☒ Full Board Meeting: ☐

CERTIFICATION

The study is acceptable on scientific and ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This re-approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL

The University of Saskatchewan Biomedical Research Ethics Board reviews above minimal studies at a full-board (face-to-face) meeting. Any research classified as minimal risk is reviewed through the delegated (subcommittee) review process. The initial Certificate of Approval includes the approval period the REB has assigned to a study. The Status Report form must be submitted within one month prior to the assigned expiry date. The researcher shall indicate to the REB any specific requirements of the sponsoring organizations (e.g. requirement for full-board review and approval) for the continuing review process deemed necessary for that project. For more information visit http://www.usask.ca/research/ethics_review/.

REB ATTESTATION

In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. This re-approval and the views of this REB have been documented in writing. The University of Saskatchewan Biomedical Research Ethics Board has been approved by the Minister of Health, Province of Saskatchewan, to serve as a Research Ethics Board (REB) for research projects involving human subjects under section 29 of The Health Information Protection Act (HIPA).

Appendix H: Exercise Protocols for Wrist Fracture Patients

Wrist Fracture Exercises While Casted

These exercises are given to prevent or reduce stiffness that can develop while you are casted.
They should be done very gently without increasing pain at the fracture site.
Do each exercise 5 times holding the stretch for 5-10 counts at least 5 times daily.

Wrist Fracture Exercises While Casted, Wrist Fracture Exercises While Casted



1. Sit or stand with good posture
2. Bend neck forward as shown

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1. Sit or stand with good posture
2. Keeping face forward, tip ear toward shoulder

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1. Sit or stand with good posture
2. Turn head to each side.

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1. Stand with arms at sides
2. Pinch shoulder blades together as shown

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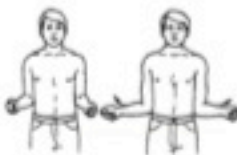
1. Stand with arm relaxed at your side
2. Raise your affected arm up overhead as far as you can

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1. Stand with arms relaxed at your side
2. Raise your affected arm up to the side as far as you can

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1. Stand with arms at sides, elbows bent as shown
2. Rotate arms outward, keeping elbows bent

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1. Stand with your affected arm straight, palm of hand facing forward as shown
2. Bend elbow as far as you can and then straighten it as much as you can

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1. Try to straighten your fingers as much as you can within the limits of the cast



1. Bend your fingers and attempt to make as tight a fist as you can within the limits of the cast

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1. Try to touch the thumb to the tip of each finger as best you can within the limits of the cast



1. Bend your large knuckle joints while keeping your fingers straight like a shelf.



1. Hold your fingers straight.
2. Bend your fingers without bending your large knuckle joints (like a claw).



1. Bend your fingers into as much of a fist as you can within the limits of the cast.

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6 Week Post Fracture Exercises

Repeat each exercise 3-5 times, 5 times a day. Hold for 15 seconds.

If you have an increase in pain which does not return to the pre-exercise level within 2 hours or have trouble sleeping at night, you have done too much. Reduce frequency to 3 times a day.

-
1. Begin with thumb facing up
 2. Turn palm upward keeping elbow at side



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-
1. Begin with thumb facing up
 2. Turn palm of hand downward keeping elbow at side



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-
1. Bend affected wrist as shown



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-
1. Bend affected wrist as shown



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Built on Tools® RG

1/2



1. Lay affected hand flat on table as shown
2. Turn hand inward toward thumb as far as you can

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1. Lay affected hand flat on table as shown
2. Turn hand outward toward little finger as far as you can

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1. Begin with palm of affected hand flat on table
2. Keep palm on table but lift fingers up off table

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1. Begin with palm of affected hand flat on table
2. Spread fingers as far apart as you can

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1. Fist
Make a tight fist. Try to bend all of your finger joints as much as possible.



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Built on Toolset RG

2/2

9 Weeks Post Fracture Exercises

Repeat each exercise 3-5 times, 3-5 times/day with 15 second holds. Use your other hand to increase the stretch. If you have an increase in pain which does not return to pre-exercise levels within 2 hours or have trouble sleeping at night, you have done too much.



1. Hold affected wrist as shown
2. Bend the wrist until you feel a stretch
3. Add making a loose fist keeping the wrist bent and elbow straight

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1. Hold your hands together as shown
2. Bend the wrist until you feel a stretch

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1. Hold affected wrist as shown, making sure to keep fingers straight
2. Bend the wrist and fingers upward until you feel a stretch keeping your elbow straight

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1. Place affected wrist flat on table as shown
2. Use the other hand to bend the wrist inward (toward thumb) until you feel a stretch

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Built on Tools® RQ

1/2



1. Place affected wrist flat on table as shown
2. Use the other hand to bend the wrist outward (toward little finger) until you feel a stretch

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1. Turn palm of affected hand upward as shown
2. Use the other hand on wrist to help so that you feel a stretch. Keep your elbow at your side and your upper arm still.

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1. Turn palm of affected hand downward as shown
2. Use other hand on wrist to help so that you feel a stretch. Keep your elbow at your side and your upper arm still.

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1. Bend the fingers of the affected hand with the other hand as shown until you feel a stretch
2. Make sure that all of the joints of the fingers are bending, including the knuckles

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1. Place affected hand flat on the table as shown
2. Press down as shown with the other hand until you feel a stretch

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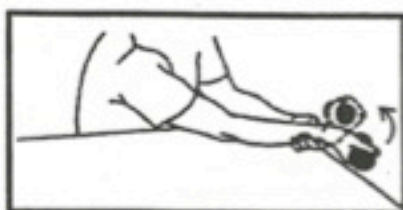
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2/2

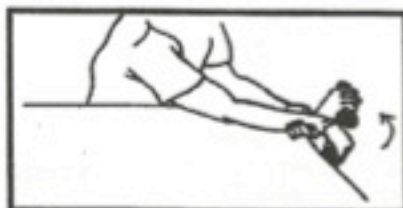
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NINE WEEKS POST FRACTURE STRENGTHENING PROGRAM

- Complete each Exercise 10-12 times, once a day.
- These exercises should cause fatigue not PAIN. If you are experiencing sharp pain during the exercise, stop and proceed to the next exercise.
- Start with a 1-2 lb. weight and gradually increase to 3-5 lbs.
- If you have an increase in pain which does not return to the pre-exercise level within 2 hours or if you have trouble sleeping at night, you have done too much. Reduce weight by 50%.
- After one week increase to two times a day.



- Support arm as shown – hold weight in hand
- Slowly curl wrist upward
- Hold for a count of 2 and slowly lower



- Support arm as shown – hold weight in hand
- Slowly curl wrist upward
- Hold for a count of 2 and slowly lower



- Support arm as shown
- Hold weight by the end as shown
- Slowly rotate forearm to a palm up position
- Hold for a count of 2 and slowly return to starting position



- Support arm as shown
- Hold weight by the end as shown
- Slowly rotate forearm to a palm down position
- Hold for a count of 2 and slowly return to starting position



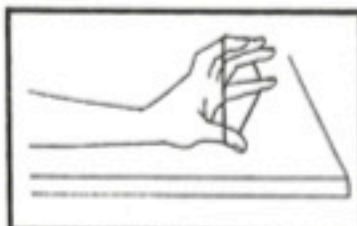
- Use a soft ball, sponge, face cloth or play doh.
- Squeeze firmly and hold for a count of two
- Relax hand and repeat



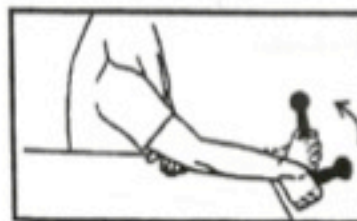
- Use a soft ball, sponge, face cloth or play doh.
- Hold between thumb and 1st two fingers
- Squeeze together and hold for a count of two
- Relax hand and repeat



- Use a soft ball, sponge, face cloth or play doh.
- Hold between thumb and side of index finger
- Squeeze together and hold for a count of two
- Relax hand and repeat



- Use an elastic band
- Place around tips of fingers and thumb
- Straighten fingers
- Relax hand and repeat



- Support arm as shown
- Hold weight by the end as shown
- Bend hand up slowly
- Hold for a count of 2 and slowly lower

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Appendix I: Cando Digi-Flex Handgrip Trainer



Appendix J: Training Log for Experiment 4

CAST Study: Training Log										
Name: _____										
WEEK	Session 1			Session 2			Session 3			Comments
	Sets x Reps	Resistance (grip color)	Date	Sets x Reps	Resistance (grip color)	Date	Sets x Reps	Resistance (grip color)	Date	
Example	3 x 8	Green	Oct. 4th	3 x 8	Green	Oct. 6th	3 x 8	Green	Oct. 8th	No troubles
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										

Appendix K: Patient Rated Wrist Evaluation

PATIENT RATED WRIST/HAND EVALUATION

The questions below will help us understand how much difficulty you have had with your wrist/hand in the past week. You will be describing your average wrist/hand symptoms over the past week on a scale of 0-10. Please provide an answer for **ALL** questions. If you did not perform an activity, please **ESTIMATE** the pain or difficulty you would expect. If you have never performed the activity, you may leave it blank.

1. PAIN																																		
<i>Rate the average amount of pain in your wrist/hand over the past week by circling the number that best describes your pain on a scale from 0-10. A zero (0) means that you did not have any pain and a ten (10) means that the pain is the worst possible (i.e worst you have ever experienced or that you could not do the activity because of pain).</i>																																		
RATE YOUR PAIN:	None									Worst																								
At rest	0	1	2	3	4	5	6	7	8	9	10																							
When doing a task with a repeated wrist/hand movement	0	1	2	3	4	5	6	7	8	9	10																							
When lifting a heavy object	0	1	2	3	4	5	6	7	8	9	10																							
When it is at its worst	0	1	2	3	4	5	6	7	8	9	10																							
<table style="width: 100%; border: none;"> <tr> <td style="width: 50%;">How often do you have pain?</td> <td style="width: 10%; text-align: center;">0</td><td style="width: 10%; text-align: center;">1</td><td style="width: 10%; text-align: center;">2</td><td style="width: 10%; text-align: center;">3</td><td style="width: 10%; text-align: center;">4</td><td style="width: 10%; text-align: center;">5</td><td style="width: 10%; text-align: center;">6</td><td style="width: 10%; text-align: center;">7</td><td style="width: 10%; text-align: center;">8</td><td style="width: 10%; text-align: center;">9</td><td style="width: 10%; text-align: center;">10</td> </tr> <tr> <td></td> <td style="text-align: center;">Never</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td style="text-align: center;">Always</td> </tr> </table>											How often do you have pain?	0	1	2	3	4	5	6	7	8	9	10		Never										Always
How often do you have pain?	0	1	2	3	4	5	6	7	8	9	10																							
	Never										Always																							

Please turn the page.....

2. FUNCTION											
A. SPECIFIC ACTIVITIES											
<p><i>Rate the amount of difficulty you experienced performing each of the items listed below - over the past week, by circling the number that describes your difficulty on a scale of 0-10. A zero (0) means you did not experience any difficulty and a ten (10) means it was so difficult you were unable to do it at all.</i></p>											
	No Difficulty										Unable To Do
Turn a door knob using my affected hand	0	1	2	3	4	5	6	7	8	9	10
Cut meat using a knife in my affected hand	0	1	2	3	4	5	6	7	8	9	10
Fasten buttons on my shirt	0	1	2	3	4	5	6	7	8	9	10
Use my affected hand to push up from a chair	0	1	2	3	4	5	6	7	8	9	10
Carry a 10lb object in my affected hand	0	1	2	3	4	5	6	7	8	9	10
Use bathroom tissue with my affected hand	0	1	2	3	4	5	6	7	8	9	10
B. USUAL ACTIVITIES											
<p><i>Rate the amount of difficulty you experienced performing your usual activities in each of the areas listed below, over the past week, by circling the number that best describes your difficulty on a scale of 0-10. By "usual activities", we mean the activities you performed before you started having a problem with your wrist/hand. A zero (0) means that you did not experience any difficulty and a ten (10) means it was so difficult you were unable to do any of your usual activities.</i></p>											
Personal care activities (dressing, washing)	0	1	2	3	4	5	6	7	8	9	10
Household work (cleaning, maintenance)	0	1	2	3	4	5	6	7	8	9	10
Work (your job or usual everyday work)	0	1	2	3	4	5	6	7	8	9	10
Recreational activities	0	1	2	3	4	5	6	7	8	9	10
APPEARANCE- OPTIONAL											
How important is the appearance of your hand? <input type="checkbox"/> Very Much <input type="checkbox"/> Somewhat <input type="checkbox"/> Not at all											
Rate how dissatisfied you were with the appearance of your wrist/hand during the past week.											
	0	1	2	3	4	5	6	7	8	9	10
	No										Complete
	Dissatisfaction										Dissatisfaction
Any other comments?											